3-23-2017

A Framework for Analyzing and Discussing Level of Human Control Abstraction

Clifford D. Johnson

A FRAMEWORK FOR ANALYZING AND DISCUSSING LEVEL OF HUMAN CONTROL ABSTRACTION

Clifford D. Johnson, Captain, USAF

AFIT-ENV-MS-17-197

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

AFIT-ENV-MS-17-197

A FRAMEWORK FOR ANALYZING AND DISCUSSING LEVEL OF HUMAN CONTROL ABSTRACTION

THESIS

Presented to the Faculty

Department of Systems Engineering and Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Systems Engineering

Clifford D. Johnson, BS

Captain, USAF

March 2017

AFIT-ENV-MS-17-197

A FRAMEWORK FOR ANALYZING AND DISCUSSING LEVEL OF HUMAN CONTROL ABSTRACTION

Clifford D. Johnson, BS

Captain, USAF

Committee Membership:

M. Miller, PhD
Chair

D. Jacques, PhD
Member

Maj. C. Rusnock, PhD
Member

Acknowledgments

My advisor, Michael Miller, Ph.D., was very supportive throughout the development and execution of this thesis. His guidance was crucial to creating this document and helping me through my entire systems engineering program. I would like to express my gratitude for all of the work he put into editing, talking through ideas, guiding me through the process, and all of his other efforts to aid creating this thesis.

Clifford D. Johnson

Table of Contents

List of Figures

Page

List of Tables

AFIT/GSE/ENV/17--xx

Abstract

As autonomous features become pervasive, control strategy research continues. Levels of Autonomy (LoA) provide a method for describing function allocation between operators and autonomous system elements. Unfortunately, LoA does not provide the user interface designer a clear method to distinguish among interface concepts which impose varying levels of operator workload or result in predictable human or system performance changes. This limitation arises as LoA does not distinguish functions which impose significant verses insignificant human workload. For example, a car with autonomous emergency breaking performs breaking at the highest Level of Autonomy. However, this function does not affect the primary decisions made by an automobile driver and automating this function alleviates little, if any, human workload. The current research suggests an alternate classification scheme, specifically Level of Human Control Abstraction (LHCA). LHCA describes how an operator controls a system based on the control tasks performed and the level of decisions made by the operator verses the system. This thesis will discuss five levels within this framework: Direct Control, Augmented Control, Parametric Control, Goal Oriented Control, and Mission Capable Control. Real world and hypothetical systems can be categorized within this framework, potentially providing a framework that is directly related to human workload and performance.

A FRAMEWORK FOR ANALYZING AND DISCUSSING LEVELS OF HUMAN CONTROL ABSTRACTION

I. Introduction

1. General Issue

In a document titled “America’s Air Force: A Call to the Future” and signed by the Chief of Staff of the Air Force, General Mark A. Welsh, III, several strategic directions are proposed for the Air Force. Among these strategic directions are increased investment in game changing technologies; including unmanned systems, and autonomy (Welsh, 2015). This vision is enhanced by a document titled “Autonomous Horizons”, signed by then Chief Scientist of the Air Force, Mica Endsley. Dr. Endsley states that this document “describes an evolutionary progression that obtains the best benefits of autonomous software working synergistically with the innovation of empowered airmen” (Endsley, 2015). Therefore, design tools which enable the creation of systems which support this synergism are necessary.

For example, robust methods are required to enable the robust control of complex modern vehicles and tele-robots when control decisions are shared between the operator and the system itself. In the past, the concept of Level of Autonomy (LoA) has been relied upon as a potential method to understand the authority granted to the autonomy within human-machine teams. However, this concept has not provided a robust tool for describing or evaluating human-machine systems and has come under significant scrutiny. In 2012 the Defense Science Board (DSB) released a document entitled “The Role of Autonomy in the DoD Systems.” This report recommends that the DoD suspend the use of conceptual frameworks focused on levels of autonomy. Instead this report recommends the development of a new framework that: focuses on capabilities, identifies which cognitive tasks have been delegated to the human verses the system, and makes system level tradeoffs visible (Office of the Under Secretary of Defense for Acquisition Technology Logistics, 2012). With this guidance, it is clear that a framework is needed by the DoD to satisfy these requirements.

2. Background

The concept of creating automated systems to has been studied for many years. System designers have used automation to improve productivity, efficiency, safety, operator workload, and to permit the control of more complex systems (Scerbo, 1996).

A commonly cited concept within the field of automation is the 10 Levels of Automation (LoA) developed by Sheridan. The levels deal with the amount of decision authority the automation has relative to the human (Sheridan, 2011).

Sheridan's concept of LoA focuses on the level of authority to make decisions allocated to the computer, not the level of detail of the decisions. This is an important distinction because delegating some decisions to a computer may have a large impact on the human while others may not. An example of a system with the highest possible LoA is automatic headlights on an automobile which turn on when they detect low ambient light. With this example the system does not require approval from the operator or give a veto option to the operator before initiating the headlights. However, an automatic headlight system does not have a very strong impact on the operator's workload or any other human performance consideration. The LoA framework fails to categorize systems along practical lines which are important to both system operators and system designers.

3. Problem Statement

A framework for system categorization which meets the criteria laid out by the DSB does not exist. This lack of a framework creates barriers to research into cognitive task allocation as an independent variable and leveraging findings from past research to create system improvements (Office of the Under Secretary of Defense for Acquisition Technology Logistics, 2012).

4. Research Objectives

The goal of this research is to develop and present a conceptual framework for categorizing the control of vehicles and tele-robotics which meets the recommendations of the DSB as well as to assess the applicability and usefulness of that framework. The levels of this framework should be defined by the allocation of cognitive functions, and decisions, to either the human or the system. Each level within the framework should have an additional layer of decision making reallocated to the system from the human. The framework should be structured to empower designers and decision makers with the capability to make system level tradeoffs more visible.

5. Methodology Overview

The methodology of this research has two aspects, first to establish the breadth of applicability of the proposed conceptual framework and second to show the framework makes system level tradeoffs visible.

A series of real world systems across several domains were analyzed within the framework. Each system was described in sufficient detail, then each of its control configurations were categorized within the framework. This process demonstrated that the framework can be applied to a plethora of systems in use today. It also served to illustrate similarities between systems controlled at the same tier within the framework, establishing a justification for conclusions about the cost and benefits related to each level.

Three hypothetical systems which could be configured to operate at each level within the framework were also analyzed. This process served to provide precise examples of how a system could be controlled at each tier, solidifying the boundaries between each level. Additionally, traits associated with each level were explored during the hypothetical system analysis.

6. Assumptions

The proposed conceptual firework is assumed to apply only to vehicles and telerobotics. Other types of systems may benefit from similar analysis on the level of detail of operator control inputs. However, the focus of this research is the control of primary motion of vehicles and telerobotics.

Additionally, an assumption exists that as a vehicle or telerobotic system is controlled at a lower level of detail the operator will require less attention to control that system effectively. This assumption was based on knowledge of system control and published literature.

7. Scope

This research is confined to introducing the conceptual framework, then establishing its usefulness by demonstrating its breadth of applicability and the potential relationship between the framework and system performance as well as Human Systems Integration (HSI) impacts. In developing the current conceptual framework, it was necessary to make a number of assertions regarding operator attention and workload based upon prior experience and published literature; however, verification of these assertions were outside the scope of the current research.

8. Organization of Thesis

This thesis is organized into six chapters. The first chapter is an introduction. The second chapter is a literature review. The third chapter introduces the proposed framework, defining and describing it. The fourth chapter describes the methodology for demonstrating the framework's breadth of applicability and ability to make system level traits visible. The fifth chapter contains the analysis of the framework, as well as systems analyzed under the framework. The sixth chapter contains conclusions and recommendations for further research.

II. Literature Review

1. Overview

Automation, autonomy, adaptive automation, and levels of autonomy or automation (LoA) are important aspects of vehicle and telerobotic control. A review of these concepts, research in these areas, and methods used for analyzing autonomous systems motivated the development of the framework proposed in this research.

2. Automation Discussion

Automation has been used across many industries to improve productivity, quality, and efficiency. As Scerbo points out, the aviation industry has successfully used cockpit automation, showing effective improvement in flight times, fuel efficiency navigation, and pilot perception. He also states that automation can reduce human variability and human errors while increasing operations flexibility and allowing the control of more complex systems (1996). The benefits of automation are numerous, obvious, and ubiquitous throughout the modern world.

As Unmanned Aerial Systems (UAS) become more ubiquitous, manpower demands for controlling those UASs will undoubtedly increase without the development of significant innovation. In "Unmanned Aircraft Systems Roadmap 2005-2030" the Office of the Secretary of Defense (OSD) specifically calls for the ability of a single pilot to control multiple UASs simultaneously (US DoD, 2005). There is a myriad of issues involved with bringing this vision to reality. Some of these issues will, no doubt, be resolved with control automation, as Scerbo asserts that more complex systems can be controlled through the implementation of automation (1996).

Overall, automation has many potential benefits to the DoD and society at large. However, negative aspects also exist. A difficult to avoid aspect of automation is the potential loss of engagement by the system operator. As automation increases, the operator often changes from actively engaged in controlling the system to monitoring the system as the automation performs many primary control tasks. Regrettably, humans are not good at vigilance tasks, such as system monitoring, and this often leads to degraded system performance (Parasuraman, 1986). In addition to struggling with vigilance tasks, humans can lose skills associated with manual operation if only automated operations are used (Wickens, Hollands, Banbury, & Parasuraman, 2015). Situation awareness (SA) can also deteriorate during the mission as operators are removed from decision loops (Scerbo, 1996). Finally, in some circumstances, operator workload can increase with increased automation. Scerbo states that when a system is automated, in some cases, when operations require low supervision the system functions well, but when the system is stressed the automation can hinder operations (1996).

3. Automation and Autonomy Differentiation

This chapter discusses automation and autonomy in detail, therefore they will each be clearly defined. Unfortunately, the literature in this area is inconsistent on the use of these terms. Specifically, some articles within the literature apply the term "level of automation" (Sheridan, 2011) while others apply the term "level of autonomy" when discussing a single framework known as LoA (Proud, Hart, & Mrozinski, 2003). Vagia's thorough literature review paper provides the following definitions and strategies for differentiation of these terms. Automation describes a system that completes a task previously completed by a human, while autonomy refers to the capability of a system to determine the proper course of action and execute that action without operator intervention (Vagia, Transeth, & Fjerdingen, 2016).

This intermixing of definitions within the literature is important to discuss because in this research, as with Vagia's literature review, the term level of autonomy is used even though the previous researchers themselves used either the phrase "level of autonomy" or "level of automation". This is done because the researchers were referring to the same concept and it allows for easier comparison of taxonomies proposed by researchers. References to the term autonomy or automation independent of the phrase LoA will adhere strictly to the definition given by Vagia and colleagues.

4. LoA from Literature

The first pioneers of the concept of LoA were Sheridan and Verplank. Their 1978 paper laid the foundation for this concept (Sheridan & Verplank, 1978). Later in his 2011 literature review Sheridan more clearly explains the levels, as shown in Table 1.

Table 1 - Sheridan's LoA

Level	Description
1	The computer offers no assistance: Human must take all decisions and actions
2	The computer offers a complete set of decision/action alternatives
3	Narrows the selection down to a few
4	Suggests one alternative
5	Executes that suggestion if the human approves
6	Allows the human a restricted time to veto before automatic execution
7	Executes automatically, then necessarily informs the human
8	Informs the human only if asked
9	Informs the human only if it, the computer, decides to
10	The computer decides everything and acts autonomously, ignoring the human

(Sheridan, 2011)

A reader will note that each level of Sheridan's 10 LoAs increases the amount of decision authority allocated to the automated agent, and similarly decreases the requirement for operator approval of those decisions. At level 1, the agent does nothing, at level 10, the agent does everything. In between, the agent needs less and less approval before initiating an action. That is, the agent is assigned increasing levels of autonomy for making and executing a decision.

Although many researchers have tried to create taxonomies describing levels of autonomy and automation (Clough, 2002; Draper, 1995; Endsley, 1987; Endsley & Kaber, 1999; Endsley & Kiris, 1995; Lorenz et al., 2001; Ntuen & Park, 1988; Proud et al., 2003; Riley, 1989; Sheridan & Verplank, 1978), Sheridan and Verplank were the first. Subsequent attempts to define the levels are based on their concept of allocating additional decision authority to the agent, and similarly reducing the need for operator approval of those decisions. There are two notable exceptions to this, they are Chen, Haas, & Barnes (2007) and Milgram, Rastogi, & Grodski (1995), who partitioned the decision space differently as discussed in section 4.2.

Following Sheridan, Endsley's 1987 taxonomy applies four LoA. Endsley uses the phrase "Allocation of Roles Between the Expert System and The Pilot" to name these levels. The levels include:

Level 1: the system makes recommendations to the pilot which he may choose to act on,

Level 2: the system makes recommendations which it will carry out if the pilot concurs,

Level 3: the system makes recommendations which it will carry out unless the pilot vetoes, or

Level 4: the system acts in an automatic fashion with the pilot completely out of the loop.

(Endsley, 1987)

Interestingly, in a 1999 paper by Endsley and Kaber, while citing this 1987 paper Endsley reiterates this taxonomy, but titles it as a LoA hierarchy, labeling each level, providing a slightly different definition of each level, and including a fifth level. The reiterated taxonomy is:

Level 1: manual control - with no assistance from the system;

Level 2: decision support - by the operator with input in the form of recommendations provided by the system;

Level 3: consensual artificial intelligence (AI) - by the system with the consent of the operator required to carry out actions;

Level 4: monitored AI - by the system to be automatically implemented unless vetoed by the operator; and

Level 5: full automation with no operator interaction.

(Endsley & Kaber, 1999)

The reader will note that Endsley's 1987 taxonomy is quite similar to Sheridan and Verplank's taxonomy. Endsley uses maximum and minimum levels with manual control and fully autonomous control, just as Sheridan, but with fewer intermediate levels. These similarities between Endsley's and Sheridan's levels carry throughout later iterations of LoA taxonomies created by these and other researchers (Vagia et al., 2016).

The concept of LoA has also been applied to different aspects of a task. In their paper, Parasuraman, Sheridan, and Wickens examine tasks at a detailed level, using the four-stage model of human information processing. The four stage model consists of sensory processing, perception/working memory, decision making, and response selection. They state that each of the four stages can be assigned to a system and automated. When the stages are assigned to a system, the resulting functions are correspondingly named: information acquisition, information analysis, decision and action selection, and action implementation. When these functions are automated the types of automation are referred to as: acquisition automation, analysis automation, decision automation, and action automation. Their analysis separates a task into subtasks associated with each of the stages. Furthermore, they examine which of these subtasks should be allocated to either the human or the system.

5. Effects of LoA from Literature

Several studies have been conducted on the effects of LoA on workload and system performance (Endsley & Kaber, 1999; Kaber & Endsley, 2004). Kaber and Endsley's 2003 study found that the LoA was the most important factor in determining performance and SA. Kaber and Ensley state that LoA was an important influence on task performance and situational awareness (SA). At the low end of the LoA spectrum performance improved while at the high end SA was improved (Kaber & Endsley, 2004).

From Kaber and Endsley's study one sees that the interactions between LoA, SA, performance, and workload are not simple and straightforward. In their 1999 and 2003 research, Kaber and Endsley used yet another taxonomy of LoA with 10 levels. For brevity this taxonomy will not be fully described, but their chosen taxonomy is similar to Sheridan and Verplank's original 1978 LoA taxonomy. Their research shows that as LoA increases; workload remains stable, SA is degraded, and overall system performance improves. However, this only held true up to intermediate LoAs. They state that the physical implementation of the operator's decisions was advantageous while performance was reduced when higher level cognitive tasks were allocated to the system (Endsley & Kaber, 1999). Endsley & Kaber posit that the reason for poorer performance when automating higher level cognitive functions was the operator's loss of focus on task execution and the self-doubt in their own decisions.

6. Alternative Related Taxonomies from Literature

All of the LoA taxonomies so far described deal with the authority given to the system with respect to the level of approval the operator provides over the system's decisions. These taxonomies do not directly address the level of detail of decisions allocated to the system or what decisions remain with the operator. This is a problem because in many modern systems, especially when real time operation is critical, Sheridan's LoA would be 10 for many component technologies even though the operator is still responsible for making decisions to control the systems on a moment to moment basis. Importantly, the LoA framework fails to differentiate along lines which have a meaningful effect on system performance and the amount of operator attention required for proper system control. Ideally, a framework would differentiate such that the highest level on the scale corresponded with a dramatically reduced workload and overall demand placed on the operator for system control.

The fact that component technologies can operate at level 10 even though the operator remains critical in the control loop can be easily illustrated. For example, once set, the cruise control on a car does not request permission to adjust the throttle to maintain speed up a hill, it simply increases power as necessary. In this example the operator is still fully engaged in the task of driving, both selecting the proper vehicle speed and making steering control inputs, but the lower level task of setting the proper throttle valve position has been fully automated. There are many examples of low level tasks that have been completely delegated to systems operating at Sheridan's LoA 10, but the operator remains heavily engaged with the operation of the system. Consequently, the effect of the automation on the operator's overall workload is limited. A framework has not yet been discussed that describes the important aspect of level of detail of control, or level of control abstraction.

Milgram discusses a different taxonomy that focuses on the level of control which is automated. Within his paper, Milgram refers to this taxonomy as both "Levels of Autonomy" and "Taxonomy of autonomy in remote operations." Milgram's work examines the control of robots, decomposing the level of control into five levels. At the lowest level, Manual Teleoperation, the operator remains completely in the loop; making every decision and controlling every motion performed by the robot. At Level 2, Telepresence, Milgram suggests "some form of master-slave control system, where all actions of the master arm initiated by the human operator are mimicked by the slave manipulator" (1995). That is, the human operator communicates exactly how the robot should move, then the robot determines the servo inputs required to achieve that movement. Level 3 is Direct/Agent Control, with "the human operator acting as a director of the task performance and the telerobot serving as the agent" (Milgram et al., 1995). At this level of control, the human operator provides specific, task level, instructions to the robot, which the robot then performs. Supervisory Control is Milgram's next level where "the human remains in the loop but has no authority to act."(Vagia et al., 2016). Unfortunately, Milgram fails to clearly define Supervisory Control, as does Vagia in her 2016 review of his work. One possible interpretation of Supervisory Control might be a system where the human operator provides goal level instructions to the robot, without taking direct control of the robot to accomplish those goals. Milgram is also vague regarding his highest level of control, Autonomous Robotics, but Vagia describes this level as “the human gets out of the loop” (2016). This could be taken to mean that the autonomous robot must interpret its environment to decide upon the goals it must achieve and the works to achieve these goals. Figure 1 provides a graphical depiction of Milgram’s LoA taxonomy.

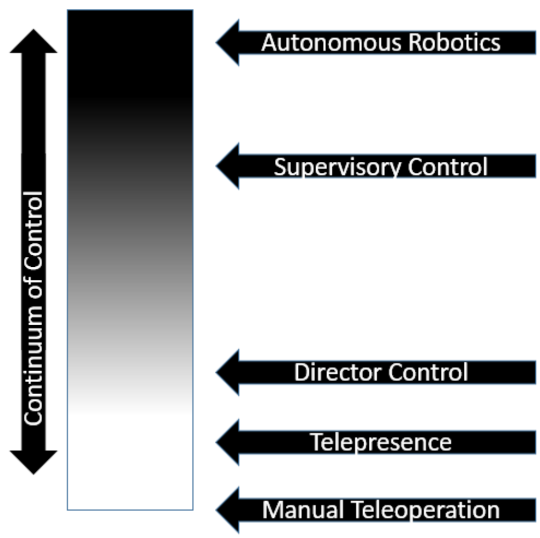

Figure 1 - Milgram’s Taxonomy of Autonomy in Remote Operations, adapted from original paper (Milgram et al., 1995)

Another way of thinking about LoAs relating to teleoperation is depicted in a figure by Chen, which has been reproduced in Figure 2 (Chen et al., 2007). Chen does not directly propose a new taxonomy; however, this graphic includes three different types of control. Chen also does not refer to the different types of control as different LoA or even suggest a hierarchy. In fact, Chen provides this as a control structure for a human operator where the human operator is able to exercise different levels of control, depending upon their needs (Chen et al., 2007). For example, such a control scheme might enable to human operator to balance their workload and their need for precise control.

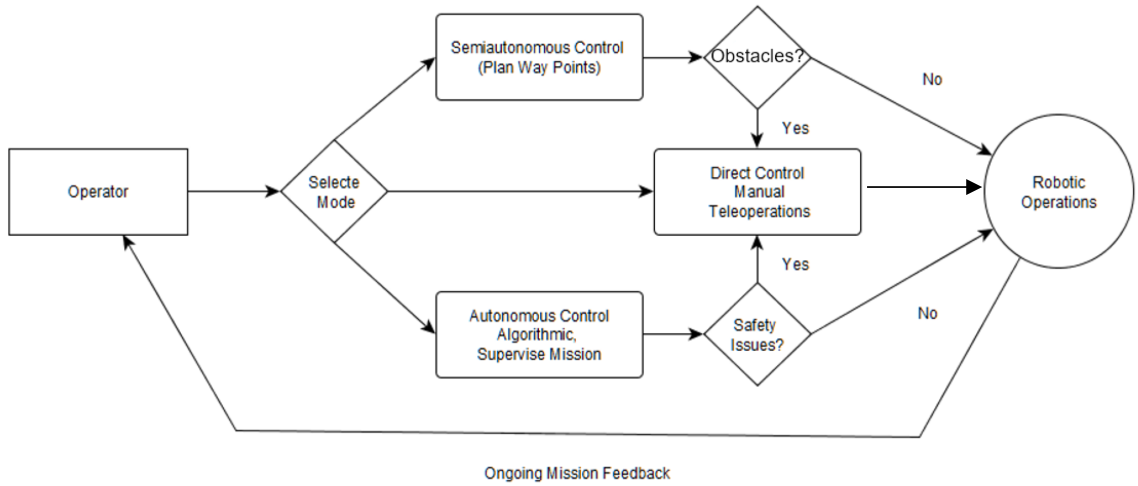

Figure 2 – Graphic based on Chen's Teleoperation Graphic (Chen et al., 2007)

One possible interpretation of the three control types which Chen calls "Direct Control," "Semiautonomous Control," and "Autonomous Control" will be described here. Direct Control is the operator determining the exact position and movements of the system. Semiautonomous Control is the operator setting small incremental goals for the system to accomplish (i.e., specifying precise tasks to be performed). Autonomous Control is the operator assigning goals to the system, then permitting the system to determine how to achieve those goals (Chen et al., 2007).

Milgram and Chen's work is included here for two reasons, first to give an alternative conceptual viewpoint of LoA from the literature and second because they approach the concept of level of control abstraction that this research focuses on. Neither of these two researchers directly discuss a generalized framework for discussing the level of operator control, but their ideas about control occurring at different levels of task detail are incorporated within the proposed framework.

7. Adaptive or Adaptable Automation

An important concept to discus in the context of automation, and especially LoA, is adaptive or adaptable automation. Adaptive automation is a system in which the automation adjust over time due to inputs form the operator or the environment (Sheridan, 2011). Scerbo states that adaptive automation enables the control tasks delegated to the system or the operator to change with time (1996). Vagia points out that some of the human performance issues associated with automation, including complacency as well as reduction in both situational awareness and operator skill, can be reduced or resolved by implementing adaptive automation (2016).

One issue with adaptive automation is knowing when to apply it. A concept for adaptive automation includes monitoring human performance for degradation and increasing automation as performance decreases has been experimented with (Scerbo, 1996). Unfortunately, this concept has the flaw of being reactive, that is, the system can only implement adaptive automation once performance has degraded. Another approach adapts automation based on workload, which is useful because it can be anticipated situationally (Scerbo, 1996). For example, a pilot expects to have higher workload during takeoff and landing than during the cruise phase of flight.

The agent that would determine what LoA is appropriate for any given situation is referred to as an allocation authority (Sheridan, 2011). That entity would use one of the methods described to determine the appropriate LoA for the current situation, and then perform “dynamic function allocation” to adjust the division of labor between the operator and the system (Vagia et al., 2016).

The concept of Adaptive Automation is important to consider because if implemented a system’s function allocation and LoA are not static. This adaptive automation adds an additional layer of complexity to the concept of LoA and may add additional utility to systems which implement it. A framework for considering adaptive automation and various trigger methods has been provided by Feigh and colleagues. This framework provides a discussion of alternative triggers for adaptive automation (Feigh, Dorneich, & Hayes, 2012) .

8. Evaluation of a Framework

In his 2014 paper “Why the Fitts list has persisted throughout the history of function allocation” de Winter analyzes Fitts list of 11 statements to be used in determining proper functional allocation between either a human or a machine (de Winter & Dodou, 2014; Fitts, 1951). To conduct the analysis de Winter treats Fitts list as a scientific theory, evaluating it against a list of six criteria which were originally developed for the cognitive sciences by Jacobs and Granger (Jacobs & Grainger, 1994). These criteria were later used by Pitt et. al. to pick between alternative theoretical explanations of scientific observations (Pitt, Myung, & Zhang, 2002). De Winter argues that by evaluating Fitts list as a scientific theory for functional allocation the same six criteria can be used to assess Fitts list. Those criteria are stated in Table 2.

Table 2 - Framework Evaluation Criteria

Criteria	Description
Plausibility	Are the assumptions of the model plausible?
Explanatory adequacy	Is the theoretical explanation reasonable and consistent with what is known?
Interpretability	Do the model and its parts make sense? Are they understandable?
Simplicity	Does the model capture the phenomenon in the least complex manner?
Descriptive adequacy	Does the model provide a good description of observed data?
Generalizability	Does the model predict well the characteristics of new, as yet unobserved data?

(de Winter & Dodou, 2014)

As this method has been applied to analyze Fitts' list as a scientific theory, this same analysis method could be applied to evaluate any proposed framework as a scientific theory.

9. Conclusion

The concept of LoA is one which has many aspects. Numerous researchers have created LoA taxonomies focused on how much authority a system has over its area of control, but there has been very little analysis on the effects of the level of detail of control. As noted by the 2012 DSB cited earlier, the LoA framework does not focus on capabilities, cognitive functional delegation between the operator and the system, or make system level trades visible (Office of the Under Secretary of Defense for Acquisition Technology Logistics, 2012). Further, increases in LoAs do not necessarily imply decreases in human workload, improvements in human SA, or improvements in human performance. Therefore, there is a need for an alternate classification method which addresses a portion of these shortcomings of the existing frameworks.

III. Conceptual Framework Proposal

This chapter focuses on proposing a conceptual framework for identifying cognitive functional responsibilities between a system and an operator as suggested by the DSB with the goal of defining a hierarchy which is expected to differentiate systems based upon the degree of human attention required. The proposed conceptual framework examines this subject from a human-centric, as opposed to system-centric, perspective. The framework focuses on how an operator is controlling a system rather than a classification for the system itself. Levels within the framework are differentiated by the level of detail of control inputs made by the operator and are not dependent on system specifications. The appropriate level of detail for the control inputs an operator provides is an important aspect of system design. The level of detail of control inputs may affect both operator workload and overall system performance. In addition, different types of tasks require different levels of detail of control.

Several informal frameworks for describing the level of detail for control inputs have been proposed (Chen et al., 2007; Endsley, 2015; Milgram et al., 1995). The goal of this research is to present and analyze a conceptual framework which satisfies the recommendations of the DSB. This framework should also facilitate the research and analysis of the level of detail of operator control inputs for vehicle and tele-robotic systems.

1. Theory

There have been several attempts to describe the level of detail of operator control inputs in the past. The three proposals were given by Chen, Milgram, and Endsley. Each proposal provided a means of describing the control of systems, permitting the human operator to relinquish detailed control of the system under specific conditions (Chen et al., 2007; Endsley, 2015; Milgram et al., 1995).

Chen's proposal was very informal and, as noted in the previous chapter, was presented through a figure within her paper on tele-operated robots. A modified version of this figure is shown in Figure 2 (Chen et al., 2007). The figure includes three "control options" and discussion of the figure within Chen's article included a recommendation for the appropriate option to use if obstacles or safety issues were present. The first option was "Direct Control", which included the descriptive terms manual and teleoperations. The second "Semiautonomous Control," was described as planning way points. The third option was "Autonomous Control" which included the descriptive terms algorithmic and supervise mission. Chen did not provide any additional detail to describe these control levels and did not propose a classification framework for control. In fact, Chen's use of roughly defined terms for discussion of this topic illustrates the current requirement for a conceptual framework describing levels of the detail of control.

Milgram proposed a "Taxonomy of autonomy in remote operations" which has five levels and ranges from "Manual Teleoperation" to "Autonomous Robotics" (Milgram et al., 1995). Milgram includes a brief description of each level within the taxonomy shown in Figure 1. In this taxonomy, each increase in the level along the continuum implies a corresponding decrease in the level of detail the operator must provide to control the tele-robot.

Endsley proposed a taxonomy of "Control Granularity" as an aspect of a system's autonomy (Endsley, 2015). Each level of control given requires a different level of detail of instructions from the operator. Endsley predicts that operator workload should decrease at higher levels of control granularity (Endsley, 2015). Figure 5 below shows a diagram from "Autonomous Horizons" published by the USAF Office of the Chief Scientist, which illustrates Endsley's Control Granularity framework.

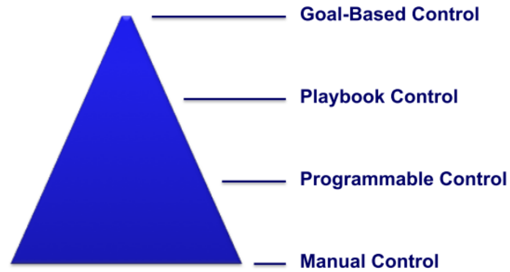

Figure 3 – Endsley's Control Granularity (Endsley, 2015)

Milgram and Endsley's proposals each suggest a description of human control granularity in which systems are classified based upon processes which roughly align with the granularity of control undertaken by the operator to control the system.

2. A Framework for Analyzing Level of Human Control Abstraction (LHCA)

The purpose of developing a conceptual framework for describing the level of detail for operator control inputs is two-fold. First, to develop a vocabulary from which to describe, discuss, understand, and contrast different systems of control. Second, a conceptual framework can be used to make predictions about the human performance effects of a control system during the design phase. Therefore, any useful conceptual framework must be able to classify different levels of control and there must be characteristic traits associated with each level that apply across various systems and ideally across various classes of systems.

This research proposes the Levels of Human Control Abstraction (LHCA) conceptual framework to describe the level of detail for operator control inputs. The framework has five levels, including: 1) Direct Control, 2) Augmented Control, 3) Parametric Control, 4) Goal Oriented Control, and 5) Mission Capable Control. As LHCA increases, the level of specificity of control inputs required from the operator decreases.

The LHCA is determined instantaneously based on the level of detail of control inputs given by the operator at a specified instant. As such, this is not a framework for classifying a system, but a framework for classifying the level of detail of human control required at any moment in time. A system may permit the operator to interact with it at any one of these levels at any moment in time but the LHCA is not, necessarily, a static attribute of the system. Instead, a given LHCA might correspond to a system state or configuration, rather than to a system.

The LHCA are defined as follows:

LHCA 1 - Direct Control occurs when the operator controls every aspect of the system, including actual control surface positions or motor power. During Direct Control the operator provides continuous control inputs and is responsible for all aspects of system operation. Examples of systems that operate at LHCA 1 are 1940s era aircraft or the simplest possible fixed wing remote control aircraft.

LHCA 2 - Augmented Control occurs when the operator gives control inputs commanding desired actions, the system then makes final determinations about control surface positions or motor power. Many, although not all, modern fly-by-wire systems are operated with Augmented Control. During Augmented Control the operator provides continuous control inputs and is responsible for guiding the system through maneuvers. The system is responsible for interpreting the operator inputs to adjust control surface positions or motor power. Examples of systems that operate at LHCA 2 are an F-117 Nighthawk or a multi-rotor UAS.

For clarification, it should also be noted that not all fly-by-wire systems operate the same, some are controlled at LHCA 1 and others LHCA 2. Some simply brake the physical connection between the pilot's controls and the control surfaces, passing the control inputs electronically to control surface actuators but not adjusting the inputs for environmental data. This type of non-augmented fly-by-wire system would be an example of Direct Control, not Augmented Control because the operator is still determining the exact position of the control surfaces and engine settings. For precision, within this research, Direct Control type fly-by-wire systems are referred to as "non-augmented fly-by-wire" and Augmented Control type fly-by-wire systems are referred to as "fly-by-wire."

LHCA 3 - Parametric Control occurs when the operator inputs desired parameters that the system should meet, the system then uses onboard sensors and control algorithms to meet those parameters. During Parametric Control the operator gives discrete control inputs. The operator is responsible for safety monitoring, including obstacle avoidance, even when the system is operating correctly without any faults. An example of a system being operated at LHCA 3 is a commercial airliner with autopilot activated. Examples of parameters the operator may input would be altitude, airspeed, heading, waypoints, or a combination of these.

LHCA 4, Goal Oriented Control occurs when the operator inputs desired goals the system should meet, the system then makes all required decisions to meet those goals. A goal is a task without follow-on instructions beyond ‘notify operator when complete.’ During Goal Oriented Control the operator gives discrete control inputs. The operator's monitoring role is reduced to planning the next goal and monitoring for system failures as, when functioning properly, the system can complete the goal without further guidance. An example of a system operating at LHCA 4 is a DJI Phantom 4 Pro, a commercially available recreational multi-rotor UAS, executing the “ActiveTrack” goal. This goal consists of keeping a specified target centered in the camera’s field of view, avoiding obstacle collisions, and following the target until “ActiveTrack” is disengaged.

LHCA 5, Mission Capable Control occurs when the operator enters pre-launch mission goals at a level of detail which, when combined with standard operating procedures (SOPs) and rules of engagement (ROEs), are sufficient to accomplish the mission. At this level, the system operates independently and autonomously after the operator initiates the mission. During Mission Capable Control the operator gives discrete control inputs before the mission begins. The operator has no mandatory monitoring role during mission execution. An example of a system operating at LHCA 5 is an autonomous car that travels to a desired location with no inputs from the driver other than the desired destination.

3. Rules and Guidelines for the LHCA framework

The LHCA is determined instantaneously based on the control inputs and responsibilities of the system operator at any given time as a system can transition from being controlled at one level to another. This is a common occurrence that routinely happens during the operation of many modern systems. The transition from one LHCA to another can be initiated by either the operator or by the system, triggered by predetermined criteria. An example of one of these transitions across LHCA is the initiation of an aircraft's autopilot system. Initially, the operator flies the aircraft with continuous control inputs, at either LHCA 1 or 2, depending on the system. The operator then activates the aircraft autopilot and begins controlling the aircraft using Parametric Control, LHCA 3. The operator may command a course, an altitude, and an airspeed, the autopilot system will manipulate the control surfaces and engine power to meet those parameters.

An example of involuntary, or system controlled, transition across LHCA is the activation of an F-16's Automatic Ground Collision Avoidance System (Auto-GCAS). During normal flying conditions, with the autopilot disabled, an F-16 is controlled at LHCA 2. Control inputs are given by the operator, then a fly-by-wire system translates the inputs, combined with environmental data, such as pressure and airspeed, then sends signals to the control surface actuators. However, if the onboard Auto-GCAS system detects an impending ground collision, the aircraft will transition to LHCA 3, Parametric

Control. The system commands the control surfaces to level off the aircraft and maintain safe flight parameters. This transition from LHCA 2 to LHCA 3 can occur without a command from the operator.

As was previously discussed, LHCA is determined based on the level of detail of control inputs given by the operator. A potential area of confusion which must be examined closely is the difference between a powered assist to manipulate a system verses a less specific control input. To illustrate the difference, examine the simplest remote control aircraft. The operator controls the aircraft with a transmitter which has pair of joysticks, as shown in Figure 4. The left joystick controls the throttle with forward and backward motions, the rudder with left and right motions. The right joystick controls the elevators with forward and backward motions, the ailerons with left and right motions. The remote-control aircraft receives control inputs from the handheld transmitter. The receiver on the aircraft is connected to servos that manipulate the control surfaces. Even though the operator is not physically moving the control surfaces, the operator is directly determining their position. There is not a determination made by the remote-control aircraft as to the position of what the control surfaces should be, the servo position is entirely determined by the position of the joysticks on the transmitter. Therefore, the system is being controlled at LHCA 1, Direct Control, even though there is not a physical link between the operator and the control surfaces.

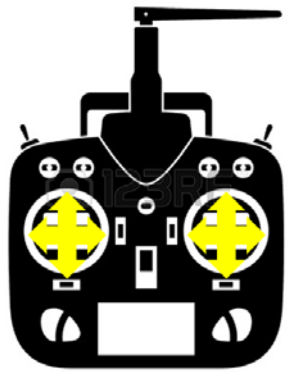

Figure 4 – Remote Control Aircraft Transmitter, arrows signal joystick movements, modified from (“Vector - vector remote control rc transmitter black icon,” 2017)

Another situation to be considered in the determination of an operator’s LHCA is the manipulation of several controls simultaneously, causing potential confusion about the operator’s current LHCA. This issue is resolved by examining the operator’s most detailed control input and assigning the LHCA based on that aspect of control. Consider an operator driving a car equipped with cruise control, but not initially engaged. The driver is operating both the steering wheel and the throttle with a high level of detail, directly controlling the steering angle of the tires while simultaneously controlling the vehicle’s throttle. Even if the car has power steering, the car is still being operated at LHCA 1 because the power steering is an example of a powered assist to manipulate a system. When the operator engages the cruise control the operator is still directly determining the steering angle of the tires, but is now controlling the vehicle’s throttle indirectly using the vehicle’s speed as a parameter to be maintained. The LHCA can be determined by using the most detailed aspect of control. In this case the LHCA is still Direct Control.

The formalized rules for determining LHCA are:

1) LHCA is determined instantaneously based on the level of detail of control inputs given by the operator.
2) LHCA is determined by the most detailed control input given by the operator.

4. LHCA Decision Tree

The decision tree shown in Figure 5 assists in determining an operator's current LHCA. This decision tree captures the rules and definitions described earlier in this chapter. A user can simply answer each question down the tree until they have arrive at the appropriate LHCA.

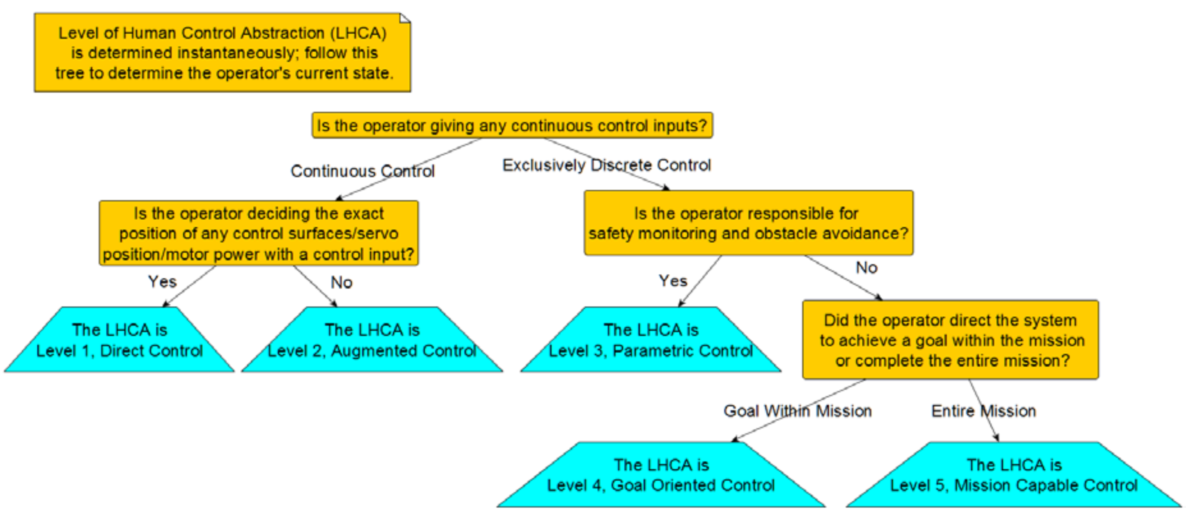

Figure 5 - LHCA Decision Tree

This decision tree should be used to assist in classifying the LHCA a system is being controlled with. For illustrative purposes, examples of systems being operated at each LHCA are examined below:

1) A simple motor boat – A photo of this system is shown in Figure 6 for clarity. Figure 6 does not show the motor boat being controlled at all, however it does illustrate the control capabilities of the boat. The decision tree analysis will assume that the example motor boat is being controlled by a single operator traveling from one location to another.
    a. Question 1: Is the operator giving any continuous control inputs? **Answer: Continuous control, the operator is giving continuous control inputs for both yaw and motor power, the only two possible control inputs.**
    b. Question 2: Is the operator deciding the exact position of any control surfaces/servo position/motor power with a control input? **Answer: Yes, the operator is deciding both the exact motor power and exact angle of thrust vectoring.**
    c. Based on this analysis, the motor boat is operated at LHCA Level 1, Direct Control.

Figure 6 – A simple motor boat ("Small Motor Boat Waiting Ferry Passengers Stock Photo," 2017)

2) Multi-rotor UAV – A photo of this system is shown in Figure 7 for clarity. The operator of this system uses joysticks to control the movement of this UAV. An internal processor receives the joystick inputs and translates them into rotation speeds for each motor.

   a. Question 1: Is the operator giving any continuous control inputs? **Answer: Continuous control, the operator is giving continuous control inputs for yaw, pitch, role, and throttle.**

   b. Question 2: Is the operator deciding the exact position of any control surfaces/servo position/motor power with a control input? **Answer: No, the operator is inputting desired motions for the UAV, but the internal processor is determining the motor power for each motor based on those inputs.**

   c. The multi-rotor is operated at LHCA Level 2, Augmented Control.

Figure 7 – A multi-rotor UAV ("Drone multicopter in field," 2017)

3) A commercial airliner at cruising altitude - During this phase of flight the operator of this system typically employs the autopilot system to control the aircraft. The autopilot system has Lateral Navigation (LNAV), Vertical Navigation (VNAV), and auto-throttle capabilities. The operator inputs a desired heading, altitude, and air speed then the autopilot acts to achieve those parameters. The operator is still responsible for safety of flight even while the autopilot is activated.

   a. Question 1: Is the operator giving any continuous control inputs? **Answer: Exclusively discrete control, the operator has given discrete control inputs.**

   b. Question 2: Is the operator responsible for safety monitoring and obstacle avoidance? **Answer: Yes, the operator remains responsible for avoiding collisions with other aircraft.**

   c. The LHCA for a commercial airliner being operated with autopilot is Level 3, Parametric Control.

4) A modern car executing an auto-park maneuver - During this phase of operation the operator has delegated all aspects of control to achieve the goal of parallel parking to the car. While from a liability standpoint the operator is still responsible for safety, from the perspective of task distribution responsibilities the system is responsible for safety monitoring. The operator's overall mission was to travel from point A to point B not simply to park the car.

   a. Question 1: Is the operator giving any continuous control inputs? **Answer: Exclusively discrete control, the operator has given the discrete control input to park the car.**

   b. Question 2: Is the operator responsible for safety monitoring and obstacle avoidance? **Answer: No, the operator has simply specified the goal to park the car near the current location and the car is responsible for avoiding collisions.**

c. Question 3: Did the operator direct the system to achieve a goal within the mission or complete the entire mission? **Answer: Goal within mission. The operator specified the goal to park the car near the current location, not travel all the way from point A to point B.**

d. The LHCA for an automobile executing an auto-park maneuver as described is Level 4, Goal Oriented Control.

5) A mapping UAV - The operator specifies an area to be mapped then hands-off control to the vehicle until the UAV has mapped the area. The UAV will take off, use the global positioning system (GPS) to navigate, collect aerial photography of the area, and then return to base and land. The UAV additionally monitors for any obstacles and avoids detected obstacles.

   a. Question 1: Is the operator giving any continuous control inputs? **Answer: Exclusively discrete control, the operator has given the discrete control inputs by specifying the area to mapped.**

   b. Question 2: Is the operator responsible for safety monitoring and obstacle avoidance? **Answer: No, the operator has simply input the mission to map the specified area, the UAV is responsible for obstacle avoidance.**

   c. Question 3: Did the operator direct the system to achieve a goal within the mission or complete the entire mission? **Answer: Entire mission. The operator is hands-off until the UAV returns and does not give inputs along the way.**

   d. The LHCA of the mapping UAV is Level 5, Mission Capable Control.

These example systems illustrate the use of the LHCA decision tree at each level as shown in Figure 5.

In summary, this chapter has reviewed the background literature relevant to the level of operator control abstraction, defined the LHCA framework, provided a decision tree, and a series of examples to clarify this framework as well as illustrated the use of the decision tree.

IV. Methodology

1. Chapter Overview

The Level of Human Control Abstraction (LHCA) conceptual framework was formally introduced in the previous chapter, this chapter will propose a suitable method for analyzing the LHCA framework. The purpose of the LHCA framework is to meet the recommendations laid out by the DSB described in chapter 1 (2012). As a prerequisite to those recommendations the framework must also be shown to be applicable to systems in use by the DoD. The analysis served to demonstrate both the LHCA breadth of applicability and ability to make system level traits visible.

It must be shown that a multitude of different vehicle and tele-robotic systems can be categorized within the LHCA framework. It must also be shown to be a precise enough framework to describe differences between various operator control configurations. To these ends a series of examples were analyzed using the LHCA framework. These examples were both real world and hypothetical systems. The real world system examples were analyzed to demonstrate that many current vehicle and telerobotic systems can be categorized within the LHCA framework. The hypothetical system examples explored the precision of the LHCA framework, illustrating how changes in control result in a LHCA reclassification. The hypothetical systems chosen can be configured to be controlled at each LHCA.

The ability to make system level traits of a control configuration visible, was also illustrated through the analysis of the real world and hypothetical system examples. The benefits and disadvantages of using a specific LHCA to control a system was explored.

This trade space analysis of LHCA may help system designers to determine the appropriate LHCA for the system they are designing.

With this analysis completed, the LHCA conceptual framework was shown to provide a descriptive vocabulary for the level of detail of operator control inputs for vehicles and tele-robotic systems.

2. Analysis of Real World Systems within the LHCA Conceptual Framework

A series of real world systems which employ various levels of automation were selected and analyzed using the LHCA framework. One goal of this analysis was to illustrate that many systems across many industries, which are controlled in different ways can be analyzed within the LHCA framework. This step was undertaken to demonstrate the breadth of the framework's applicability. The other goal of this analysis was to qualitatively consider the human performance impacts of controlling a system at each LHCA. If a robust index of traits associated with the use of each LHCA were developed, system designers could reference the index to make informed design decisions with respect to how their system should be controlled.

The real world systems were selected from across industries, time periods, and levels of sophistication. The LHCA for other systems could also have been analyzed and classified, but the selection covered a breadth of control techniques under consideration for DoD and related systems.

As discussed in Chapter 3, LHCA is not necessarily a static trait of a system, but an instantaneous description of how a system is being controlled, typically associated with one or more system states. Therefore, each real world system analyzed had a detailed description of each control configuration before the LHCA was assessed. Some systems are not capable of being controlled using more than one LHCA, others can change among multiple LHCA circumstantially or as dictated by the operator. Each system analyzed included a list of LHCA an operator can use to control the system as well as a description of how the transition is accomplished.

Specific, brand name systems were chosen for this analysis instead of generic systems. This specificity was required to properly discuss how the system is controlled and properly analyze how control decisions were made with the system. A description of how these systems operate was included for each system within the analysis. A brief description of why that system was included and a system overview is given below. The systems analyzed within the LHCA framework are shown in Table 3:

Table 3 – Real World Systems Analyzed and the LHCAs provided by each system based upon the analysis

Category	System	Available Levels of Human Control Abstraction				
		1	2	3	4	5
Automotive	Volvo XC90	X	X	X		
Aircraft	P-51 Mustang	X				
	B-2 Spirit		X	X		
	F-16 Falcon		X	X		
	Airbus A300-600R		X	X		
UAG	Carnegie Mellon University, Humanoid Robot Prototype		X			
UAV	DJI Phantom 4		X	X	X	X
	PRENAV Drone System					X

1) 2017, Volvo XC90. This automobile has several subsystems that relate to vehicle control including power steering, power brakes, automatic traction control, anti-lock brakes, cruise control, adaptive cruise control, lane keeping aid, park assist pilot, and pilot assist. This vehicle was chosen because it has many features that affect the LHCA, however this vehicle is not an anomaly; most competitive automotive manufactures have equivalent systems. In the Volvo XC90, each of these subsystems relating to vehicle control can be active or inactive at any moment in time and can be operated in conjunction with several other subsystems, resulting in a large number of potential system states. Each of these features will affect the LHCA differently allowing the system to be operated at LHCA 1, 2, or 3. A discussion of how the many different subsystems influence the operator's LHCA serves to introduce LHCA categorization in a context readers are likely familiar with.
2) 1940, North American Aviation P-51 Mustang. This aircraft is completely manual and can only operate at LHCA 1, Direct Control. A detailed description of how the operator controls this vehicle demonstrates an example of a pre-computer control system.
3) 1989, Northrop Grumman B-2 Spirit. This aircraft is an example of an inherently unstable system that cannot be effectively controlled at LHCA 1. This aircraft is described as unstable because, unlike a stable aircraft, if left completely uncontrolled after a disturbance it will not return to straight and level flight. This aircraft is able to be flown by hand at LHCA 2, Augmented Control, or operated using an autopilot system at LHCA 3, Parametric Control. In addition, an accident caused by the fly-by-wire system was analyzed. This analysis demonstrated a possible disadvantage of systems controlled with a LHCA greater than 1.

4) 1976, General Dynamics F-16 Falcon. This aircraft is equipped with a fly-by-wire system, an autopilot system, and an automatic ground collision avoidance system (Auto-GCAS). These different control systems will allow this aircraft to be controlled at LHCA 2 or 3. Analysis of the transition between LHCA in this case was thought-provoking because the system can automatically transition to LHCA 3 from LHCA 2 without any input from the operator if certain criteria, such as impending controlled flight into terrain, is met.
5) 1974, Airbus A300-600R. A specific instance of an accident in this aircraft, the loss of China Airlines' Flight 140 on April 26, 1994, was analyzed. This accident was caused because the pilot was incorrect about the LHCA he was operating the aircraft with. The pilot thought he was operating the aircraft with LHCA 2, but in fact, he was operating the aircraft with LHCA 3. This analysis helped illustrate potential brittleness of autonomous systems and help to develop a design recommendation regarding LHCA transitions.
6) 2006, Manufactured by Kawada Industries, modified by Carnegie Mellon University (CMU) Humanoid Robot Prototype (HRP) (Chestnutt, Michel, Nishiwaki, Kuffner, & Kagami, 2006). This bipedal robot was modified by CMU to operate at LHCA 2, Augmented Control. Analysis of this system will help to demonstrate that the important factor in determining LHCA is the operator’s perspective of the control inputs, not the sophistication of algorithms used to implement the operator’s control.
7) 2016, DJI Phantom 4. This system is a consumer quad-rotor UAS with several features enabling it to be operated with LHCA 2, 3, 4, or 5. The versatility of control methods and broad functionality across the LHCA spectrum made it an excellent system to analyze. This analysis illustrated several key aspects of the LHCA

framework and served to illustrate the benefits of operating a system at a particular LHCA for a given goal.

8) 2016, PRENAV Drone System. This system is a cellular transmission tower inspection UAS which can only be operated at LHCA 5. Analysis of this system, specifically the design decision to only allow operation at LHCA 5, will illustrate how training and liability can affect system design requirements by establishing desired LHCA. This is an important discussion because of a potential new generation of UAVs and UAGs operating at LHCA 5 within industry and the DoD.

3. Analysis of Hypothetical Systems within the LHCA Conceptual Framework

The analysis of real world systems within the LHCA conceptual framework served to illustrate the benefits and drawbacks of operating at a LHCA and provide clarifying examples of the distinctions between each LHCA. The analysis of several hypothetical systems which can be operated across the LHCA spectrum demonstrated the precise distinction between each LHCA. Additionally, similar to the real world system analysis, the hypothetical system analysis illustrated some benefits and drawbacks of each LHCA. There were three hypothetical systems analyzed. Each system included a configuration which was operated at each LHCA. The three hypothetical systems were a small fixed wing UAV, a bipedal Unmanned Ground Vehicle (UGV), and an explosive ordinance disposal (EOD) UGV. Table 4 shows the control configurations of the hypothetical systems which were analyzed.

Table 4 - Hypothetical Systems Analyzed

System	LHCA of Control Configuration				
	1	2	3	4	5
Fixed Wing UAV	X	X	X	X	X
Bipedal Robot	X	X	X	X	X
EOD UGV	X	X	X	X	X

The hypothetical fixed wing UAV was a small (<10 lb) aircraft with a radio receiver, ailerons, elevators, rudder, and an electric motor driving a propeller. Each of the control surfaces were manipulated by electric servos. The control inputs given by the operator as well as required onboard navigational equipment and sensors was dependent on the system configuration and tied to the LHCA. For example, at LCHA 1 the autopilot will be disabled and at LHCA 3 the autopilot will be enabled. This hypothetical fixed wing UAV should be considered a baseline to which the other two hypothetical systems can be compared.

The hypothetical bipedal UGV was a five-foot-tall humanoid robot. The UGV has articulated ankle joints, knee joints, and hip joints, as well as arms to assist with balance while walking. The UGV has different systems onboard to enable control at each LHCA just as the hypothetical UAV does. The selected control configuration affects the subsystems such as optical sensors, gyroscopes, and GPS which allow the system to operate at each LHCA. Analysis of this bipedal UGV allowed consideration of how a complex, unstable system might be controlled at each LHCA.

The hypothetical EOD UGV was a rugged treaded vehicle with an arm and gripper used for manipulation of an explosive device. The analysis of this UGV allowed consideration of how a system with multiple phases of operation, transit and manipulation, could be controlled during each phase. This analysis also enabled study of each LHCA when precise and smooth detailed motion was required, as with the explosive device manipulation phase of operation.

4. Methodology for Evaluation of Framework as a Theory

The methodology described in this chapter provides a basis for evaluation of the LHCA conceptual framework. The framework was evaluated per the criteria applied by de Winter to asses Fitt's list. Those criteria were plausibility, explanatory adequacy, interpretability, simplicity, descriptive adequacy, and generalizability (de Winter & Dodou, 2014). As part of the process do determine the framework's explanatory and descriptive adequacy, traits about the control of a system which can be determined based on the LCHA were discussed.

V. Analysis and Results

1. Chapter Overview

The methodology for analyzing the LHCA conceptual framework used in this research was proposed in the previous chapter, this chapter describes the analysis. The analysis served to draw useful conclusions and generalizations about systems which are operated at each LHCA and to show that the LHCA framework has met its two goals. As described in the Chapter 3 the two goals of the LHCA framework are: 1) to develop a vocabulary from which to describe, discuss, understand, and contrast different systems of control and 2) to make predictions about the human performance effects of a control system during the design phase. In addition to meeting the goals of the framework, it will be evaluated in a fashion similar to de Winter's evaluation of Fitts list and compared to the recommendations of the DSB (de Winter & Dodou, 2014; Office of the Under Secretary of Defense for Acquisition Technology Logistics, 2012).

2. Analysis of Real World Systems within the LHCA Conceptual Framework

By categorizing systems from different domains within the LHCA framework the breadth of applicability of the framework is demonstrated. Each system analyzed in this section includes a system description sufficient to describe the control systems which influence LHCA as well as each configuration of the system categorized within the LHCA framework. The systems chosen for this analysis are listed in Table 3. Finally, several systems include an accident description and analysis which relates to the LHCA the system was operated at during the accident.

During this analysis, the LHCA Decision Tree presented in Chapter 3 will be used to determine the LHCA for each configuration of the systems.

<u>2017 Volvo XC90 LHCA analysis</u>

The first system to be analyzed is the 2017 Volvo XC90. This automobile has several subsystems that relate to vehicle control including power steering, power brakes, automatic traction control, anti-lock brakes, cruise control, adaptive cruise control, lane keeping aid, park assist pilot, and pilot assist. A brief discussion of each of these sub systems and the functionality they provide will add clarity to the analysis.

- Both power steering and power brakes are hydraulic systems which add mechanical assistance to the operator's manipulation of the tire steering angle and brake pads. The systems are active any time the vehicle's engine is on. The operator uses continuous control inputs on the steering wheel and brake pedal. The power steering hydraulic system substantially boosts the force applied to the car's steering arm which in turn sets the tire steering angle. The power brake hydraulic system boosts the force applied to the brake pad which pushes against the brake rotor to apply braking force to the tires. Importantly, neither of these systems are making determinations about what the steering angle should be or how much braking force should be applied. The operator is making the determinations regarding how the vehicle should be controlled, and simply receives a mechanical assist. This concept is similar to a lever and a fulcrum for lifting an object, the lever operator sets the position of the lever and is receiving a mechanical assist to move the object.

- Automatic traction control functions by sensing if the tire is slipping against the road surface and reducing the force applied to the wheel if slipping is detected. This system is interpreting the operator's throttle inputs and making determinations about the appropriate force to apply to the wheels for maximum performance.
- Anti-lock brakes function similar to the automatic traction control system, but with braking force instead of engine produced force. The anti-lock brake system senses if the tire is slipping against the road surface. If slippage, or skidding, is detected the anti-lock brake system cycles the brake pad force applied to the brake rotor on and off. This cycling prevents loss of vehicle control by preventing a sustained skid during emergency braking conditions (American Automobile Association Foundation for Traffic Safety, 2017).
- Cruise control functions as a simple regulator. When the operator activates the cruise control system the vehicle makes throttle decisions to maintain the current speed.
- Adaptive cruise control is similar to legacy cruise control but regulates a second parameter based upon information sensed from the environment. Once the operator has activated the adaptive cruise control system, the system will use the throttle and brake to regulate distance between the XC90 and the vehicle in front of the XC90. If there is not a vehicle in front of the automobile the system will function like the legacy cruise control system.
- Lane keeping aid is activated any time the vehicle is traveling above 45 miles per hour (mph) unless specifically deactivated by the operator. This system uses optical sensors to determine the vehicle's position between lane marker lines. If the system

senses that the vehicle is too close to the lane's edge, a small torque is applied to the steering wheel, centering the vehicle in the lane. An additional vibration indicator within the steering wheel is activated if the lane keeping aid intervenes to provide tactile feedback to the user. This system is temporarily deactivated if the operator uses the turn signals to indicate an intentional lane change.

- When activated by the operator, the park assist aid system applies optical sensors to search for a parking spot (either parallel or perpendicular) as the operator drives forward slowly. When a potential spot is detected the system will inform the operator and the operator can choose to have the system park the vehicle. The operator will then put the vehicle in reverse and give brake pedal control inputs as the system controls the steering wheel and gives braking instructions to the operator while the vehicle is parked.
- Pilot assist will control all aspects of the vehicle's travel when activated. The vehicle will control the steering wheel, brake, and throttle while the operator monitors. For legal and liability reasons the operator is instructed to stay attentive and keep a hand on the wheel, but unless the operator overrides the system all steering, brake, and throttle control inputs are provided by the pilot assist system.
- The automatic traction control, anti-lock brakes, and lane keeping aid systems are normally not activated consciously by the operator. There is a switch to disable these systems, but these systems are actively monitoring driving conditions to intervene when required under normal operational procedures. From a LHCA perspective, these systems will not affect the LHCA while monitoring, only when augmenting the

operator's control inputs. For example, during a skid, when the anti-lock braking system activates.

As shown in Table 3 this vehicle can be operated at LHCA 1, 2, or 3. The LHCA is determined by the operator activating or deactivating the subsystems described above.

First, consider a configuration where the following systems are activated: power steering, power brake, automatic traction control, anti-lock brakes and cruise control. The first question of the decision tree is "Is the operator giving any continuous control inputs?" the answer to this question is yes, continuous control, because the operator is providing continuous control inputs for the steering wheel and the brake. The second question is "Is the operator deciding the exact position of any control surfaces/servo position/motor power with a control input?" the answer to this is yes, the operator is determining the exact steering angle of the front wheels. Therefore, even though the operator has delegated direct control of the throttle control and brake control to the cruise control, anti-lock brakes, and traction control systems, the operator is still operating the vehicle at LHCA 1, direct control.

Next consider a configuration where the adaptive cruise control is activated. Again, the operator has released direct control of some aspects of control but not others. The adaptive cruise control system does not affect the steering angle of the tires. The operator is still controlling the vehicle at LHCA 1.

If the operator were to activate the park assist aid system, then the operator only provides control inputs with the brake pedal. In this case, under normal circumstances, the answer to both the first and second questions in the decision tree are yes and the

LHCA is still 1, Direct Control. However, if ice were to cause the car to skid during the parking maneuver and the anti-lock brakes were to activate, then the operator would be controlling the vehicle at LHCA 2. The LHCA changes because the only aspect of control the operator has been tasked with is now being augmented by the anti-lock brake system.

If the operator chooses to activate both the adaptive cruise control and the lane assist aid then the operator is potentially releasing direct control of all three aspects of control: the throttle, the brake, and the steering angle of the tires. For this scenario assume that the operator keeps a hand on the steering wheel as required by the manufacturer, but does not provide control inputs. The operator is only attentively monitoring the vehicle for safety. Using the decision tree to determine the LHCA the answer to the first question is no, the operator is using discrete control inputs. In this case the second question is “Is the operator responsible for safety monitoring and obstacle avoidance?” The answer to this question is yes, the operator is using the parameters of vehicle speed, distance between vehicles, and distance from the vehicle to the lane markers to control the vehicle. If a deer were to wonder onto the road the vehicle would not be capable of avoiding the obstacle. Additionally, if a sharp corner were in the road the vehicle would not be able to appropriately slow down for a safe turning maneuver. Therefore, the LHCA is Level 3, Parametric Control.

Finally, if the operator were to activate the pilot assist system and release the steering wheel then the vehicle is being operated in virtually the same way as if the active cruise control and lane assist subsystems were simultaneously activated as described above. The answers to the decision tree questions would be discrete control and yes, the LHCA is Level 3, Parametric Control.

The 2017 Volvo XC90 cannot be controlled at LHCA 4 or 5. The system cannot be operated at LHCA 4 because the operator cannot input a goal for the vehicle to achieve and then remain uninvolved with vehicle control until that goal is achieved. If, for example, the park assist system did not require operator brake inputs, when activated, the vehicle would be controlled at LHCA 4. The vehicle cannot be operated at LHCA 5 because the operator cannot input the mission and then disengage from vehicle control. If the operator could, from a stop, command the vehicle to drive to the nearest grocery store, then LHCA 5 would be possible.

Categorizing the 2017 Volvo XC90 in all of its different configurations with activated and deactivated relevant subsystems illustrates the versatility of the LHCA framework within the automotive domain. Additionally, addressing which LHCA are not attainable and why helps to show how similar systems could be analyzed under the LHCA conceptual framework.

1940 North American Aviation P-51 Mustang LHCA analysis

The operator controls this aircraft in flight by manipulating a control stick, rudder pedals, and a throttle lever. The control systems are simple, using pullies and cables to translate the operator's manipulations of the control input devices directly into physical motions of the ailerons, elevator, rudder, and the air intake throttle valve.

The answer to the first question in the LHCA Decision Tree, “Is the operator giving any continuous control inputs?” is yes, continuous control inputs. The operator provides continuous control inputs for the control stick and the rudder pedals. The answer to the second question “Is the operator deciding the exact position of any control surfaces/servo position/motor power with a control input?” is also yes. The operator has direct control over all aspects of the control surfaces and engine settings. The P-51 is a classic example of LHCA 1, Direct Control, illustrating how a simple system can be controlled directly by the operator.

1989, Northrop Grumman B-2 Spirit

The control systems of this aircraft are interesting because of the contrast to the simplicity of the P-51’s control systems. Whereas the P-51 is solely controlled by the position of the operator’s control input devices, the B-2 has a complex fly-by-wire system which interprets the position of the control devices as well as environmental data to determine the proper flight settings. Specifically, there are 24 pitot-static sensors mounted flush with the skin of the aircraft which are used to calculate air speed, altitude, angle of attack, as well as other flight data. When the operator pulls back on the control stick the flight computer combines that input with information from the pitot-static sensors to set the control surfaces in a configuration which will pitch the aircraft’s nose up. This is very different than the P-51 control system which will directly move the elevators as the operator pulls the control stick back.

This aircraft has two applicable flight modes which were analyzed within the LHCA conceptual framework. The first was with the autopilot disengaged and the second was with the autopilot engaged, maintaining specific flight parameters.

With the aircraft in the first configuration, autopilot disengaged, the answer to the first decision tree question, “is the operator giving any continuous control inputs?” is yes, continuous control inputs are being used. The answer to the second question “Is the operator deciding the exact position of any control surfaces/servo positions/motor power with a control input?” is no, the fight computer is determining those positions and settings. Therefore, the LHCA is 2, Augmented Control.

The fly-by wire system is used because of the complexity of controlling the flight of the B-2, caused by its inherent flight instability. Constant adjustments would need to be made across many control settings to control this aircraft and these control settings would place extreme workload on the pilot, assuming the pilot was capable of performing these control settings in a timely fashion. Therefore, the fly-by-wire system in this aircraft greatly reduces the pilot workload and enables this aircraft to be effectively controlled.

With the aircraft in the second configuration, autopilot engaged, the answer to the first decision tree question, “is the operator giving any continuous control inputs?” is no, exclusively discrete control inputs are being used. The answer to the second question “is the operator responsible for safety monitoring and obstacle avoidance?” is yes, the aircraft is not detecting and taking steps to avoid either stationary or moving obstacles, it is simply maintaining flight parameters. Therefore, the LHCA is 3, Parametric Control.

On 23 February, 2008 a B-2 at Andersen Air Force Base, Guam, crashed 17 seconds after takeoff because of a failure in the sensors which feed data to the flight control system. Per the official accident report moisture contaminated three of the 24 surface mounted pitot-static sensors. These sensors indicated to the flight computer that the aircraft needed to pitch the aircraft nose up. In response, the flight computer commanded the control surfaces to put the aircraft into a steep climb. The operator pushed forward on the control stick in an attempt to overcome the pitch up, but this control input was not passed to the control surfaces as the operator intended because of the corrupted pitot-static data. The aircraft's high angle of attack caused the aircraft to stall, the operators ejected, and the aircraft was lost (USAF, 2008). This accident was the most expensive Class A accident in USAF history. This mishap is an example of how, by allocating control decisions to automation, brittleness and potential faults are added to the system.

<u>1976, General Dynamics F-16 Falcon.</u>

The F-16 is equipped with three systems that are relevant to LHCA analysis. A fly-by-wire flight control system, an autopilot, and the Automatic Ground Collision Avoidance System (Auto-GCAS).

From a LHCA perspective, the fly-by-wire control system functions similar to the B-2's flight control system. By applying pressure to the control stick and rudders the operator commands a pitch, roll, or yaw rate, not specific control surface positions. Somewhat uniquely, the F-16 control stick is in a fixed position, a force meter senses the operator’s applied force to receive role and pitch control inputs. After initial testing, slight movement was added for pilot feedback but much less than a traditional control stick. The control surface positions are determined by the flight computer based on environmental data combined with pilot control inputs.

The autopilot system functions as a regulator, maintaining flight parameters entered by the operator. Pitot-static, GPS, and inertial navigation sensors on the aircraft feed flight and navigational data to the flight computer which adjusts the control surfaces and thrust to meet the operator’s commanded flight parameters.

The Auto-GCAS is intended to prevent controlled flight into ground accidents. This system is designed to prevent mishaps caused by operator’s loss of SA, spatial disorientation, loss of consciousness from over-G, and gear-up landings. The aircraft uses navigational and flight data combined with a global terrain map to determine if a collision with the ground is imminent. If the aircraft senses that a ground collision is imminent, audio and visual warnings are given to the operator. If the operator does not act to prevent the collision the Auto-GCAS will right the aircraft (wings level) and fly level on the aircraft’s last course. Auto-GCAS will relinquish control to the operator when the operator begins making control inputs after the recovery. The operator has the option to override Auto-GCAS recovery, but if no action is taken the Auto-GCAS will recover the aircraft without any input from the operator.

To analyze the F-16 within the LHCA conceptual framework three flight configurations needed to be categorized: autopilot disengaged, autopilot engaged, and Auto-GCAS active. A discussion of the responsibilities of the operator and Auto-GCAS serves to illustrate how the LHCA conceptual framework can be applied in unique control situations.

First consider the configuration where the F-16 is being operated with the autopilot system disabled and the operator using the control stick, rudder pedals, and thrust lever to control the aircraft. The operator is giving continuous control inputs, but not commanding specific control surface positions, following the LHCA Decision Tree the LHCA is 2, Augmented Control.

The second configuration considered was the operator controlling the aircraft with the autopilot engaged. The operator does not provide continuous control inputs but remains responsible for safety monitoring and obstacle avoidance tasks. Therefore, the LHCA is 3, Parametric Control.

The final configuration to consider is a scenario where the Auto-GCAS has sensed an imminent ground collision and has begun aircraft recovery. At first glance, this configuration may seem to not be able to be categorized because the operator is not providing any control inputs. However, the operator is using predetermined control inputs, parameters determining the safe recovery altitude and cursing airspeed are determined within the flight manual. Additionally, the aircraft's post-recovery heading is the heading before the Auto-GCAS was enabled. Therefore, the answer to the first LHCA Decision Tree question is "exclusively discrete control" because these control inputs are discrete not continuous.

The next question in the LHCA Decision Tree may also seem to cause an issue for the LHCA framework. "Is the operator responsible for safety monitoring and obstacle avoidance?" This may cause confusion because the operator could be unconscious when the Auto-GCAS is engaged, and yet the Auto-GCAS is not able to detect and avoid mid-air collisions with other aircraft. This begs the question, is the operator responsible for avoiding other aircraft while unconscious? In this case, yes, as the Auto-GCAS is simply meeting and maintaining flight parameters until further notice and not actively avoiding mid-air collisions. Responsibility for avoiding all obstacles that are not in the aircraft's onboard terrain map, which the Auto-GCAS depends on, falls on the operator. The gap between the Auto-GCAS capability to detect and avoid mid-air collisions, and the operator's capability to avoid them because of potential unconsciousness is a risk. The LHCA is 3, Parametric Control with a risk of mid-air collisions accepted by aircraft designers and operators.

1974, Airbus A300-600R.

The flight control systems of the Airbus A300-600R are similar to the B-2 and F-16 aircraft because it has fly-by-wire and autopilot systems. The two different flight configurations, autopilot enabled and autopilot disabled, are operated at LHCA 2 and 3 respectively. To categorize these two configurations one would apply the same logic that was used to categorize the flight configurations as the B-2 and F-16.

On 26 April 1994, an Airbus A300-600R crashed at Nagoya airport in Japan because of operator confusion about the current LHCA. The aircraft's autopilot was engaged in takeoff/go-around (TO/GA) mode by the first officer. When the pilot took control and attempted to land the aircraft manually the aircraft entered an unrecoverable stall at low altitude (Beringer & Harris, 1999). As the aircraft did a low pass over the runway (go-around) the pilot pushed forward on the yolk and reduced throttle in an attempt to land the aircraft. However, because the autopilot was engaged in the TO/GA mode the autopilot counteracted the pilot's control inputs using the aircraft's trim control surfaces which the autopilot maintained control of. The reduced throttle input given by the operator and the autopilot's trim input caused the aircraft to pitch up sharply, then stall and crash. Two hundred sixty four of 271 people onboard were killed in the accident (Ministry of Transportation, 1996).

This case is an example of an operator providing control inputs at LHCA 2 while the aircraft was in a mode where it could effectively receive control inputs only at LHCA 3. This accident highlights the need for clear communication of LHCA expectations between the pilot and aircraft.

<u>2006, HRP, manufactured by Kawada Industries, modified by CMU</u>

This bipedal robot was initially developed by Kawada industries and then modified by CMU to operate at LHCA 2, Augmented Control. The CMU HRP is controlled in real time with a joystick by a single operator. The operator moves the joystick in a direction and the HRP responds by taking steps in that direction. The operator remains responsible for determining the path of the robot to avoid obstacles. If the operator relaxes the joystick to the rest position the robot will stop and maintain balance (Chestnutt et al., 2006).

Balance is a constant challenge for the HRP because of its bipedal nature. Much like a human, standing still requires micro adjustments to maintain balance. As the robot picks up one of its two feet and moves it forward, the robot must ensure that it's center of gravity (CoG) remains positioned under the other foot to prevent a fall. The CMU HPR control scheme allows a non-technical operator to control this very complex machine by removing the operator from the balance control loop. The operator simply guides the robot in the desired direction using the joystick.

<u>2016, DJI Phantom 4</u>

This multi-rotor consumer UAS is equipped with many sub-systems which allow it to be operated at LHCA 2, 3, 4, or 5. Below, each flight configuration is described and categorized within the LHCA conceptual framework.

The default flight mode for the Phantom 4 is a fly-by-wire system where the operator uses joysticks to provide control inputs to the UAV. By manipulating the control sticks the operator is commanding pitch, role, yaw, and power settings. The operator's commands are achieved by adjusting relative power, and therefore lift, of the rotors to maneuver the UAV. Following the LHCA Decision Tree will show that in its default mode the UAV is controlled at LHCA 2.

The Phantom 4 can also be controlled by commanding flight parameters and waypoints. The operator can set waypoints using an interactive map as well as airspeed and altitude settings. When commanded, the UAV will fly on a course directly toward the waypoint at the specified altitude and airspeed, not avoiding any obstacles. Under these conditions the UAV is being operated at LHCA 3 Parametric Control, because the operator maintains responsibility for obstacle avoidance and the UAV is simply following specified parameters. (DJI, 2016)

The UAV has a relevant flight mode called “ActiveTrack.” When this flight mode is activated, the UAV will track a target with the onboard camera. As the target moves, the camera and UAV itself will move to keep the target centered in the camera’s field of view. The UAV has obstacle avoidance sensors which will help the UAV avoid both stationary and moving obstacles while tracking the target. Under these conditions the operator is controlling the UAV at LHCA 4 because the operator is not providing continuous control inputs and is not responsible for flight safety, but has not commanded an entire mission to be completed, just a goal. (DJI, 2016)

The Phantom 4 has several other flight modes which allow it to be operated at LHCA 4. A mode called “TapFly” allows the operator to tap a location on the camera’s video feed, the UAV will fly to that location avoiding obstacles on the way. When the “Return To Home” mode is activated the UAV will fly to a predetermined location if the radio connection is lost, plotting its own course and avoiding obstacles (DJI, 2016).

Finally, this UAV can be controlled at LHCA 5 using a 3D mapping function. To use this function, an operator selects the 3D mapping mode, specifies the area to be mapped, and then commands the UAV to execute the orders. The operator may adjust settings such as the number of photos to be taken per linear foot and the flight altitude which both relate to the resolution of the final 3D image. When commanded, the UAV will take off, fly to the area to be mapped, overfly and take aerial photography of the specified area on a course which the system has determined, and finally return to and land at the takeoff location. In addition, during its flight the UAV will avoid obstacles. This is considered LHCA 5 instead of LHCA 4 because the operator does not provide intermittent commands between the beginning and end of the mission. Therefore, the UAV executes the mission completely autonomously.

This type of telerobotic control, with many operational modes at different LHCA, enables the operator to control the vehicle at the desired level of detail. The UAV can be controlled with a low level of detail when the operator does not want to allocate much attention to control of the UAV. For example, if the operator wanted to record themselves performing a recreational activity they would use a mode which enabled LHCA 4. In contrast the operator may need to perform a task which requires a high level of detail of control such as slaloming between obstacles, in this case an operator would use the default flight mode and control the UAV at LHCA 2. The versatility of control options, enabling many LHCA, increases the operational flexibility of this UAV.

2016, PRENAV Drone System

The PRENAV UAS is a system which is designed to inspect hard to reach locations such as cellular and radio transmission towers or windmills. This system is specifically designed to be operated at LHCA 5, allowing laymen to operate the system. To control the UAS, the operator indicates what the inspection target is. Next the UAS plots a course and when commanded flies that course, returning to its starting location when the inspection is complete. This UAS replaces a previous generation of systems which were controlled at LHCA 2 and required a high level of operator training to operate (McSweeney, 2016).

While this UAS is interesting in itself, the primary point of interest here is that LHCA was a design requirement. It was important that a very low level of detail of control inputs be provided to the UAS by the operator. This requirement enables lower labor costs and more flexible operations for the users. As more automation is incorporated into systems, it is possible that LHCA may be a driving design requirement for many systems of the future.

Overall, the results of the analysis of existing real world systems illustrates a total of 16 system states from nine different systems within 3 different industries were successfully categorized into one of the five LHCAs. This evaluation was complete by answering the small set of questions shown in the decision tree shown in Figure 5.

3. Analysis of Hypothetical Systems within the LHCA Conceptual Framework

The presentation of hypothetical systems which can be configured to operate at each LHCA helps to show trends in the effect of LHCA on system operations and more clearly differentiates between each level. Three systems, a fixed wing UAV, a bipedal UGV, and a treaded EOD UGV with a manipulator arm and gripper, were chosen for this analysis. These hypothetical systems were chosen because they each operate in very different domains, all of which are of interest to the DoD, and illustrate how these types of systems could be operated at each LHCA.

Fixed Wing UAV

The fixed wing UAV is the first hypothetical system to be analyzed within the LHCA conceptual framework. Below, Table 5 describes each of the five configurations of the hypothetical system. The LHCA, the operator's control inputs, the relevant aspects of the control system, and an explanation of the LHCA are given for each configuration.

Table 5 – Hypothetical Fixed Wing UAV configurations

LHCA	Operator Control Inputs	Control System Description	LHCA explanation
1, Direct Control	The operator uses control sticks to control the UAV. Two joysticks control elevator, aileron, rudder, and motor power.	Signals received from the operator indicate servo positions and motor power directly.	The operator is deciding exact servo positions and motor power.
2, Augmented Control	The operator uses control sticks to control the UAV. Two joysticks control pitch, yaw, role, and thrust.	Signals received from the operator are processed by a stability control system which sets servo positions and motor power.	The operator is deciding what flight maneuvers to perform, but the stability controller is deciding exact control surface positions.
3, Parametric Control	The operator enters desired altitude, airspeed, and heading into a control panel.	Signals received from the operator, onboard navigation and flight data sensors are used to fly aircraft as desired.	The operator enters desired flight parameters, the system works to achieve those parameters. The operator remains responsible for safety.

4, Goal Oriented Control	The operator selects the pre-programed goal to return home while avoiding obstacles.	A signal to return home is received by the UAV. The UAV uses navigation tools, optical sensors, and stability control to fly 'home.' Obstacles are detected and avoided.	The operator enters a desired goal, the system determines the required actions to achieve the goal and then executes these actions.
5, Mission Capable Control	The operator selects a mission from pre-programed options, enters specific mission parameters, and commands mission execution.	The UAV receives the mission parameters from the ground station, navigates to the operational area, achieves mission goal(s), and navigates to and lands at 'home.'	The operator enters the mission, the system determines how to achieve the mission and requires no further input from the operator after the execution order.

The Direct Control, LHCA 1, configuration is controlled by the operator using two joysticks, each joystick axis controls a control surface or the motor power. In this configuration, the operator is controlling the exact settings for all aspects of control using continuous control inputs, as is expected for a system controlled at LHCA 1.

The Augmented Control, LHCA 2, configuration is also controlled with two joysticks; however, each joystick axis controls either the thrust or the role, pitch, or yaw rate. This contrasts the Direct Control configuration because the position of the control surface is not controlled by the operator, but an algorithm which considers the joystick positions as one of its inputs.

The Parametric Control, LHCA 3, configuration functions just like the autopilot systems described in the real-world system section. The operator sets flight parameters and the UAV adjusts the control surfaces and motor power to achieve those parameters.

This indirect method of control using discrete control inputs which keeps obstacle avoidance responsibilities with the operator is indicative of LHCA 3.

The Goal Oriented Control, LCHA 4, configuration allows the operator to enter one of many pre-programed goals to be accomplished mid-mission. The example ‘return to home’ is given in the Table 5 description, but any mid-mission goal would qualify for LHCA 4. The operator commands the UAV to fly to a pre-determined location designated ‘home’ and land there. Note that the command initiating this action may be a loss of radio signal. The UAV then navigates ‘home’, accepting flight safety responsibilities along the way. This configuration enables the level of human attention required to drop dramatically. The operator may be fully engaged in another activity and just receive notice when the goal is accomplished, or if some issue arises.

The Mission Capable Control, LHCA 5, configuration is controlled by the operator before takeoff. The operator gives commands for the UAV to execute a mission, specifying required parameters, the UAV then executes the mission without further control inputs from the operator. Similar to LHCA 4, in this configuration the operator’s required attention is dramatically reduced.

To further illustrate the differences between each LHCA a series of functional decomposition diagrams were developed. The series of functional decompositions was chosen to be included in the hypothetical UAV instead of other systems because this system could be operated at each LHCA, allowing a graphical illustration of each LHCA. This same exercise could be completed for any system, but the functional decomposition would have different components. Obviously, an automobile would have a different set of decomposed functions than a UAV, but the automobile's functions could also be allocated to either the operator or the system at each LHCA.

The functions associated with the flight operations of the UAV were decomposed and then allocated to either the system or the operator. The components of the UAV's Flight Operations were: Flight Control and Dynamic Mission Planning. These components were decomposed further and then allocated to the entity responsible for the leaf level function. Precise definitions of each leaf level function were described in bullet format below:

- Determine Flight Parameters – Setting the aircraft's air speed, altitude, heading, rate of climb/decent, or similar aspects of controlling the UAS
- Determine Pitch/Roll/Yaw/Thrust – Continuously choosing the desired pitch, roll, yaw, or thrust required to achieve the desired flight parameters.
- Determine Control Surface & Motor Power - Continuously choosing the desired elevator, aileron, rudder, and motor power required to achieve the desired pitch, roll, yaw, or throttle setting.
- Determine Intermediate Goals – Determine the next goal to be achieved during a mission.
- Determine Flight Path – Determine the desired course of the aircraft to achieve the intermediate goal.

Determine Obstacle Avoidance Route – Determine how the aircraft should divert from the desired flight path to avoid obstacles.

The Hypothetical UAV functional decomposition of control related duties for LHCA 1 is shown in Figure 8. When the UAV is controlled at LHCA 1 all control duties are allocated to the operator.

-

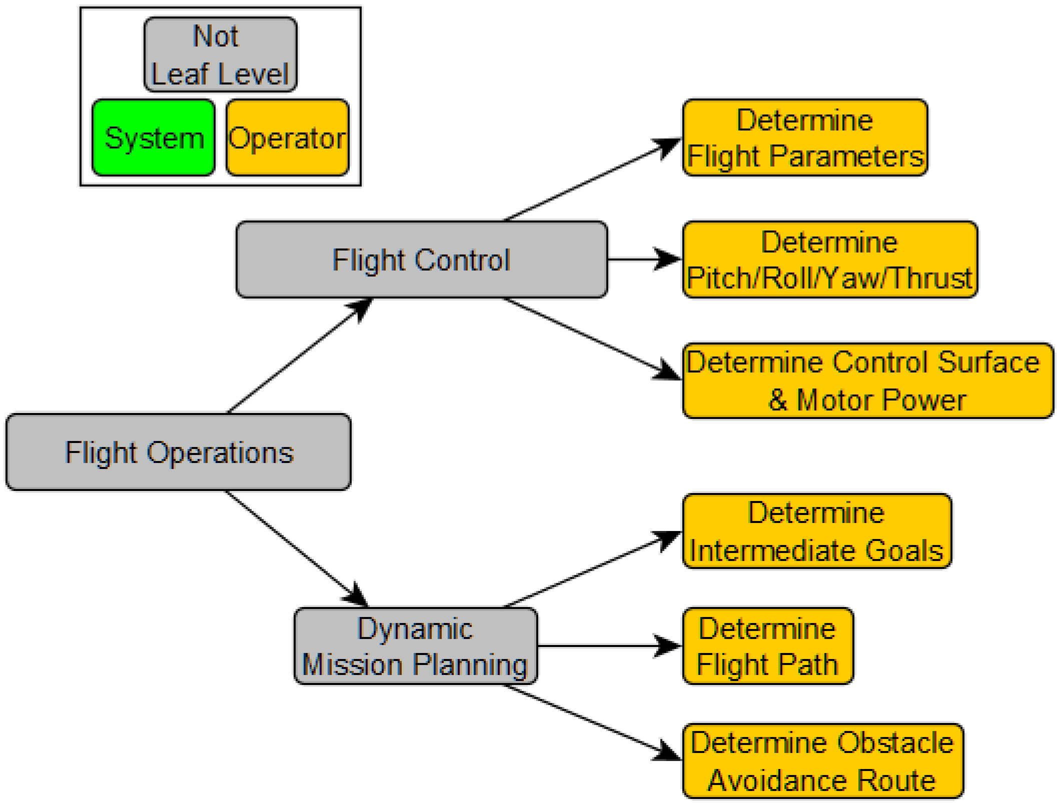

Figure 8– Hypothetical UAV Functional Decomposition of Control Duties, LHCA 1

The Hypothetical UAV functional decomposition of control related duties for LHCA 2 is shown in Figure 9. When controlled at LHCA 2, the operator is commanding pitch, roll, yaw, and thrust. The system uses these inputs as well as flight data to determine the control surface and motor power.

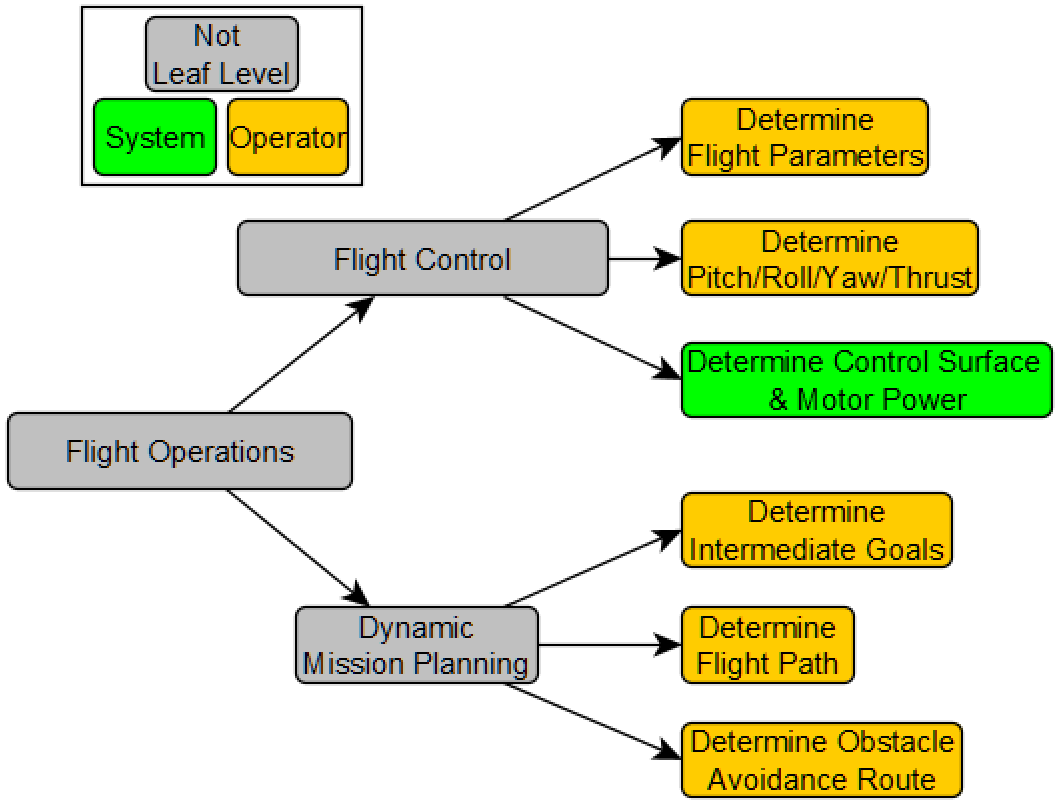

Figure 9– Hypothetical UAV Functional Decomposition of Control Duties, LHCA 2

The Hypothetical UAV functional decomposition of control related duties for LHCA 3 is shown in Figure 10. When controlled at LHCA 3, the operator is commanding flight parameters such as airspeed, altitude, and heading. The system uses these inputs as well as flight data to determine the pitch, roll, yaw, and thrust required to meet those parameters, then manipulates the control surfaces and sets motor power as required.

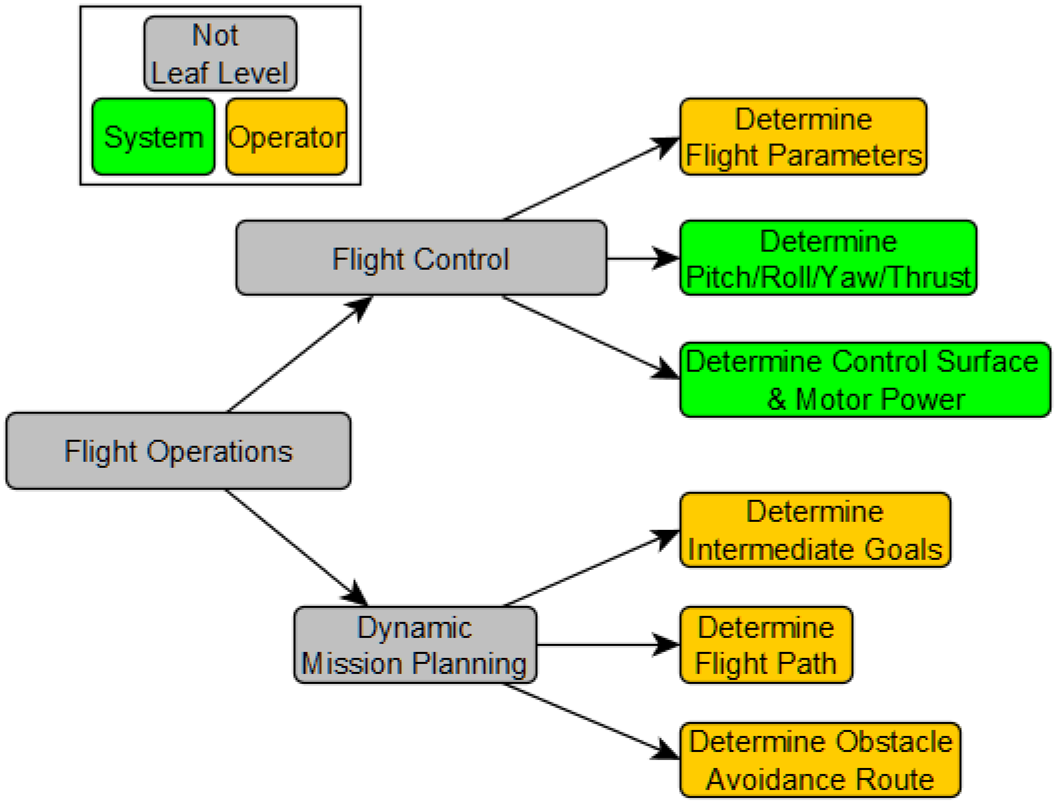

Figure 10– Hypothetical UAV Functional Decomposition of Control Duties, LHCA 3

The Hypothetical UAV functional decomposition of control related duties for LHCA 4 is shown in Figure 11. When controlled at LHCA 4, the operator is commanding intermediate goals for the system to achieve. The system must process the assigned goal and work to achieve it without further control inputs from the operator until the intermediate goal is achieved. Therefore, the system must determine its own flight path and avoid obstacles while maneuvering to achieve the goal. In addition, the more detailed flight decisions are allocated to the system as was the case for LHCA 2.

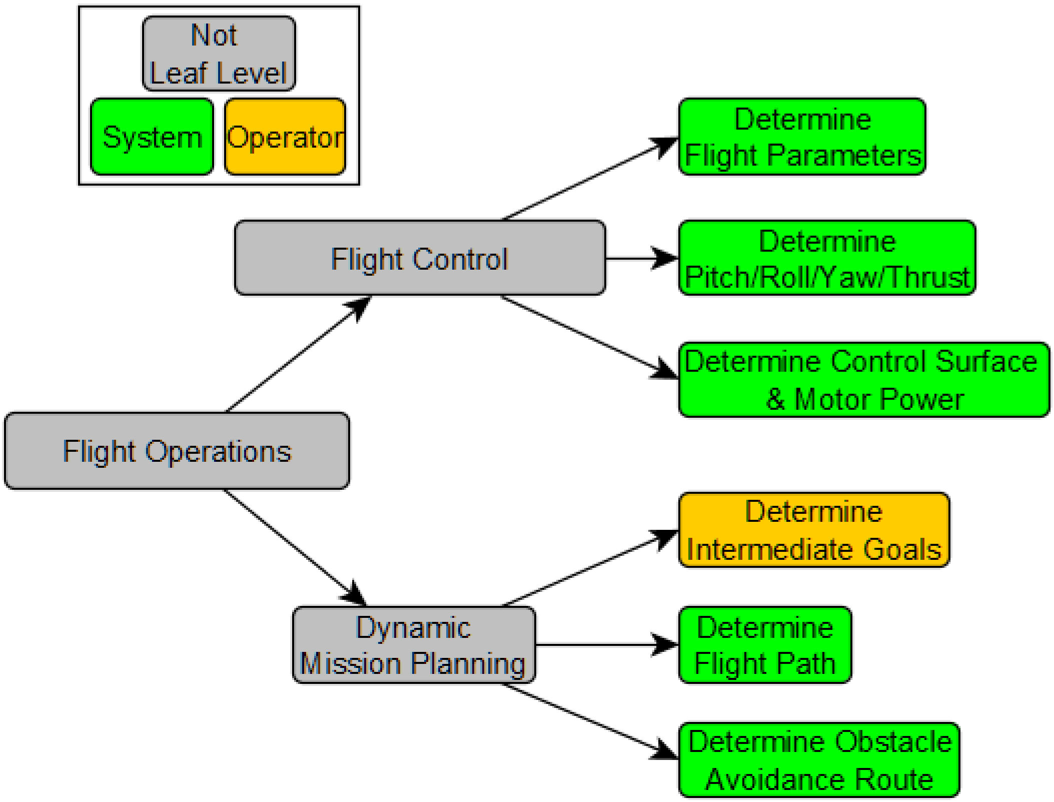

Figure 11– Hypothetical UAV Functional Decomposition of Control Duties, LHCA 4

The Hypothetical UAV functional decomposition of control related duties for LHCA 5 is shown in Figure 12. When controlled at LHCA 4, the operator commands a full mission to be completed and the system must execute autonomously. To enable this LHCA the system is responsible for setting and achieving intermediate goals on the path to accomplishing the overall mission.

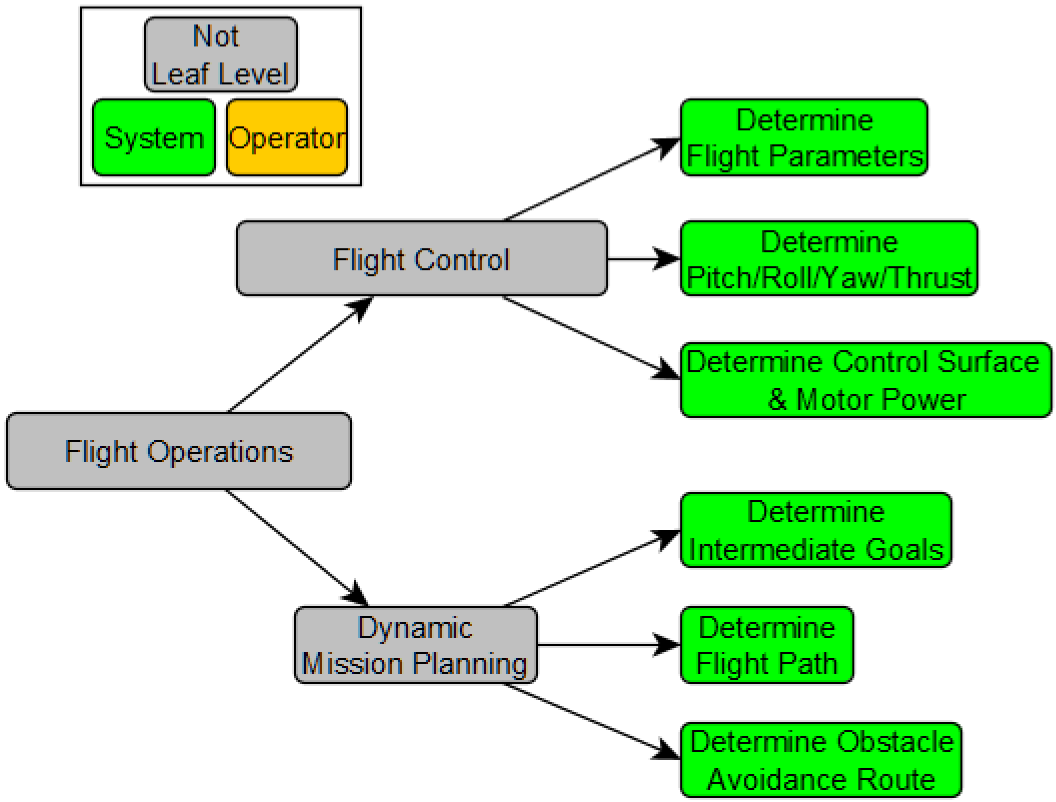

Figure 12– Hypothetical UAV Functional Decomposition of Control Duties, LHCA 5

Bipedal UGV

The next system to be considered is a hypothetical bipedal UGV which can be configured to be controlled at each LHCA. The intent of this analysis is to illustrate that complex systems are very difficult to control at LHCA 1 and to show how a system in this domain could be operated at each LHCA. Table 6 describes each of the five configurations of the hypothetical system. The overall system description is included in Chapter 4.

Table 6– Hypothetical Bipedal UGV LHCA configurations

LHCA	Operator Inputs	Control System Description	LHCA explanation
1, Direct Control	The operator must specify the position of every joint continuously.	An operator sets the position/angle of each joint continuously and maintains UGV balance.	The operator is responsible for setting the joint positions for the UGV. The operator must provide continuous input for all joints and maintain balance of the system as it maneuvers.
2, Augmented Control	The operator uses a control stick to command direction and speed of travel.	Signals received from the operator are processed by a stability control system which controls the joint positions.	The operator decides where the UGV should travel and provides continuous control inputs, but the stability controller is deciding exact servo positions.
3, Parametric Control	The operator enters desired waypoints, the operator is responsible for determining the exact walking path of the UGV.	In combination with onboard navigational sensors, parameters and waypoints are received from the operator and are used to guide the UGV through the desired path.	The operator enters the desired path of travel, the system determines the actions to take to travel along that path.
4, Goal Oriented Control	The operator selects a desired pre-programed goal to pick up a box at waypoint A and place it at waypoint B, the UGV determines the path between points A and B.	The UGV receives the operator's command and then travels to point A, detects the box, picks up the box, travels to point B, and puts the box down. Then stands by for additional instructions from operator.	The operator enters a desired goal, the system determines what actions are required to achieve that goal and then works to achieve that goal.
5, Mission Capable Control	The operator selects mission parameters from pre-programed options, enters specific mission parameters, and commands mission execution.	The UGV receives the operator's command and then executes the entire mission without additional input from the operator after execution begins.	The operator enters an entire mission, the system determines exactly how to achieve that mission and requires no further input from the operator after the execution order.

The primary point of interest with this system is that real time control of this system would be virtually impossible at LHCA 1. An operator would be required to control balance related micro adjustments manually without the aid of an active stabilizer system. This would likely exceed what an operator could realistically handle for even a simple task like walking, let alone any operational use of the UGV. The issues related to controlling this hypothetical bipedal humanoid robot at LHCA 1 are similar to issues related to controlling the B-2 as described earlier in this chapter. An operator requires the assistance of active stabilization to effectively control a complex, unstable system.

By contrast this hypothetical system could be operated at LHCA 2. This control scheme could function the same as the CMU HRP described earlier in this chapter. The operator would provide guidance through a joystick on the desired direction and speed of travel. In response to these control inputs controlling algorithms would activate the actual servos controlling joint positions and move the UGV as commanded by the operator.

When configured for Parametric Control the operator would set waypoints and speed parameters for the UGV. The stability algorithms would still be used to maintain balance and walk, but the input to those algorithms would be from the navigation computer, not the operator’s joystick as in Augmented Control. In this configuration, the UGV is not aware of obstacles, the operator is still responsible for obstacle avoidance. If the operator were to set a waypoint on the far side of a hazard, the UGV would travel directly toward the waypoint and trip on the obstacle. The operator must use waypoints to instruct the UGV on a safe path to follow during operations. Figure 13 below illustrates how the operator would need to use the waypoints to guide the UGV around any obsticles.

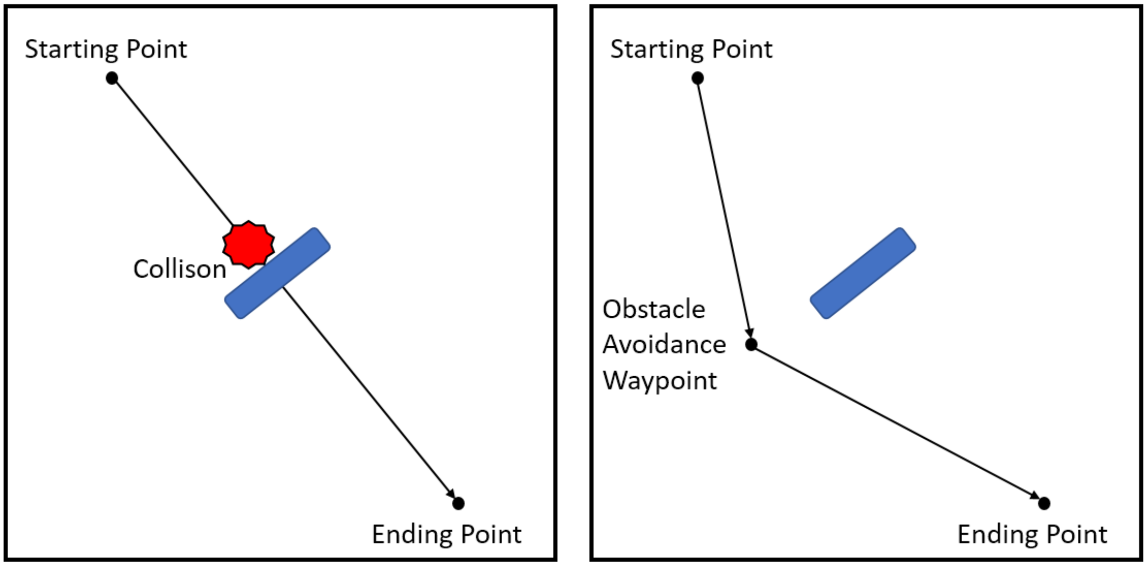

Figure 13 – Parametric Control Obstacle Avoidance

The Goal Oriented Control configuration allows the operator to command a goal. The UGV is capable of achieving that goal without additional instructions from the operator. The example given in the Table 6 is a command to move a box from point A to point B. This example is depicted in Figure 14. The operator commands the goal, then the UGV executes the goal without further instruction from the operator, even if obstacles are in the direct path. This scenario assumes that the mission for the UGV was more involved than moving the box from point A to point B. If moving the box were the entire mission, this would be an example of Mission Capable Control.

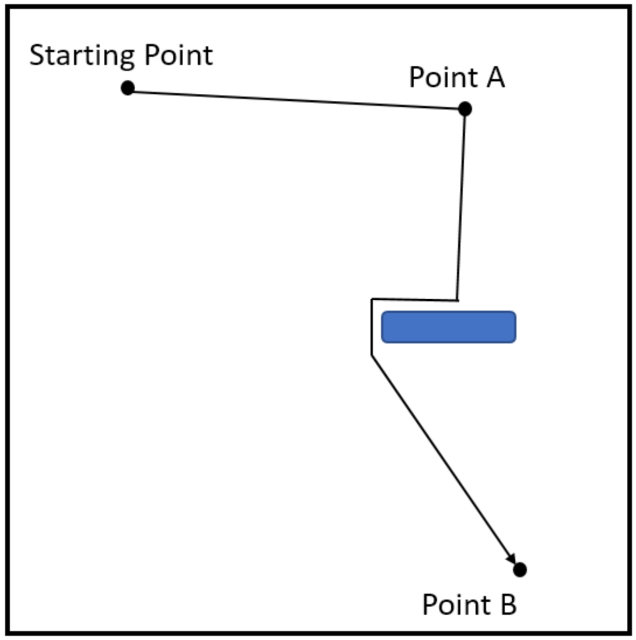

Figure 14 – Goal Oriented Control Example

If the UGV is configured for Mission Capable Control, the operator will be able to command the entire mission to the UGV. The UGV would be instructed on what must be done then would autonomously execute that mission without further guidance from the operator. For instance, the robot might be commanded to move boxes from a stack to their appropriate locations within a warehouse.

EOD UGV

This hypothetical EOD UGV is designed to be able to transport itself several hundred yards, from a safe location where it is deployed to the location of the hazardous ordinance and then manipulate the ordinance with a gripper. The two phases of operation (i.e., transit and manipulation) will be considered separately for the LHCA analysis. During the transit phase the UGV is traveling, during the manipulation phase the UGV is using the manipulator arm to grip the ordinance. Table 7 below briefly describes the hypothetical EOD UGV configurations. A photo of how this UGV may look is shown in Figure 15 below.

Table 7 – Hypothetical EOD UGV LHCA configurations

LHCA	Operator Inputs	Control System Description	LHCA explanation
1, Direct Control - Transit Phase	The operator uses 2 joysticks to control the treads independently giving the capability to move forward, backward, turn while traveling, or spin in place.	Signals received from operator indicate tread rotation motor power for each tread directly.	The operator is deciding exact servo positions and motor power for each aspect of the UGV
1, Direct Control - Manipulation Phase	A separate set of three joysticks control the robotic arm and gripper for manipulation. Each axis of motion of the joysticks controls a separate joint on the UGV.	Signals received from the operator indicate arm and gripper servo positions directly.	
2, Augmented Control - Transit Phase	The operator uses joysticks to control UGV locomotion. On board sensors detect overbalancing and prevent UGV actions that would cause a roll-over. Additionally, a stabilization system on the arm instantaneously and automatically counteracts unintentional bouncing motion in the arm during transit.	Signals received from the operator are processed by the stability control system which then passes signals along to control tread motors and arm servo position.	The operator is deciding what actions should be taken, but the arm and locomotion stability control systems are deciding exact final control inputs to the motors and servos.

2, Augmented Control - Manipulation Phase	The operator uses joysticks to control the arm, however each axis on a joystick can control a degree of freedom of motion for the UGV arm and gripper. Each degree of freedom may affect the position of multiple servos working in combination. A stabilization system ensures smooth motion of arm and gripper. Additionally, sensors on the gripper detect slippage of the explosive ordinance device and apply appropriate grip pressure to prevent slippage without applying unnecessary pressure to the ordinance.	Signals received from the operator are processed by the control system and the auto-grip system which then pass signals along to the arm and gripper servos. An example of a degree of freedom of motion is moving the end of the arm left or right, this may result in many servos working in combination to coordinate this action, for example the "wrist" of the robot arm would compensate for the sideways motion to maintain the orientation of the gripper which would be a different degree of freedom.	The operator is deciding what actions should be taken, but the arm control and auto-grip systems are deciding exact final control inputs to the motors and servos.
3, Parametric Control - Transit Phase	The operator inputs waypoints for the UGV to travel between as well as a speed to maintain. The operator is responsible for maneuvering around obstacles.	Signals received from operator in combination with onboard navigation sensors are used by the UGV to travel to the desired location.	The operator enters a desired ground path and travel parameters, the system determines what actions should be taken to achieve those parameters.
3, Parametric Control - Manipulation Phase	The operator inputs desired arm and gripper positions, then presses an "execute" button. This requires multiple iterations of the desired input then executes as the ordinance is inspected and manipulated.	Signals received from the operator in combination with onboard proprioception (knowledge of arm and gripper position) allow the UGV to move the arm and gripper to the position desired by the operator.	The operator enters discrete inputs indicating the desired position of the gripper and arm. The system manipulates the arm to achieve the desired position.

4, Goal Oriented Control - Transit Phase	The operator inputs desired end position of UGV as well as any desired areas to avoid along the potential route, such as buried landmines or enemy occupied territory.	The system uses onboard navigation data, environmental sensors, and operator's inputs to generate the route. The UGV then travels along that route with no further input from operator. The UGV will avoid obstacles along the route as that is a requirement to achieve the goal.	The operator enters a desired goal, the system determines what actions are required to achieve that goal, and finally works to achieve the goal.
4, Goal Oriented Control - Manipulation Phase	The operator selects a desired pre-programed goal, for example "grab and lift ordinance."	The system uses environmental sensors as well as proprioception to detect the ordinance, then grab and lift it.	
5, Mission Capable Control - Both Phases	The operator selects mission parameters from pre-programed options, for example "grab and lift ordinance located at Location X then carry it to Location Y and return to current location." As with LHCA 4, the operator is required to enter specific mission parameters, for example "stay out of area Z during transit." Then commands mission initialization.	The UGV receives the mission parameters from the operator, then navigates to the ordinance, achieves mission goal, and navigates back to current location.	The operator enters the desired goal of an entire mission, the system determines exactly how to achieve that mission and requires no further input from the operator after the execution order.

Figure 15 – Photograph of Hypothetical EOD UGV (“Talon EOD robot,” 2017)

Transit Phase

During the Transit Phase the Direct Control configuration of the UGV is controlled by the operator with a pair of joysticks, each joystick controls the power to one of the two treads. The operator is able to steer the UGV with differential power applied to the treads. In this configuration, the operator is responsible for all decisions regarding how the UGV interacts with its environment.

The Augmented Control configuration of the UGV is controlled similarly to the Direct Control configuration, but with the addition of safeguard and stabilization features. The operator provides the same types of control inputs, but an anti-roll system guards against overbalancing the UGV. An onboard sensor detects the vehicle’s CoG and the terrain angle. The stability system will not pass along commands which will cause a roll. This system functions similar to an anti-stall or stick shaker in an aircraft, preventing possible human operator errors. In addition, the stabilization system uses inertial sensors and servo controls to provide micro adjustments to stabilize the arm during transit. This provides an active suspension feature to stabilize the arm during transport, preventing a carried ordinance device from being unintentionally jostled.

The Parametric Control configuration is controlled similar to the hypothetical bipedal UGV's Parametric Control configuration. The operator will input waypoints and speed, then the system will travel to those waypoints. The operator remains responsible for obstacle avoidance.

The Goal Oriented Control configuration is also controlled similar to the hypothetical bipedal UGV's equivalent configuration. The operator commands a location for the UGV to travel to along with any areas to avoid, then the vehicle will make its way to the specified location.

There is not a transit phase and a manipulation phase for the Mission Capable Configuration because the UGV does not intermittently receive instructions from the operator. Instead the operator provides all relevant mission data before the before the mission begins and the UGV autonomously accomplishes the mission. For this reason the Mission Capable Configuration will not be discussed in the Manipulation Phase section below.

Manipulation Phase

In the Direct Control configuration, the operator controls every aspect of the vehicle directly. A set of three joysticks are used, each axis of the joysticks correlates to a joint on the UGV arm or gripper. Just as with all systems, in the direct control mode no "computer assistance" or "active stabilization" is provided by the UGV. Figure 16 below shows how the joints would be controlled. Each set of arrows in the LHCA 1 portion of the figure maps to an axis of one of the control sticks.

The Augmented Control configuration is also controlled with joysticks, but each joystick controls a degree of freedom of the arm and gripper instead of a single joint. This change means that when the operator provides a single control input the response on the UGV may be several servos reacting in concert. This difference is illustrated in Figure 16 below. In addition, active stabilization and auto-grip features are available. The active stabilization system reduces vibrations in the arm and ensures that motions are smooth instead of irregular. The auto-grip feature regulates the grip pressure of the UGV to prevent slippage of anything in the gripper, while at the same time ensuring too much pressure is not applied. These additional systems are examples of control at LHCA 2, the operator uses continuous control inputs to instruct the UGV how to move then a computer provides assistance to accomplish the operator's intentions effectively.

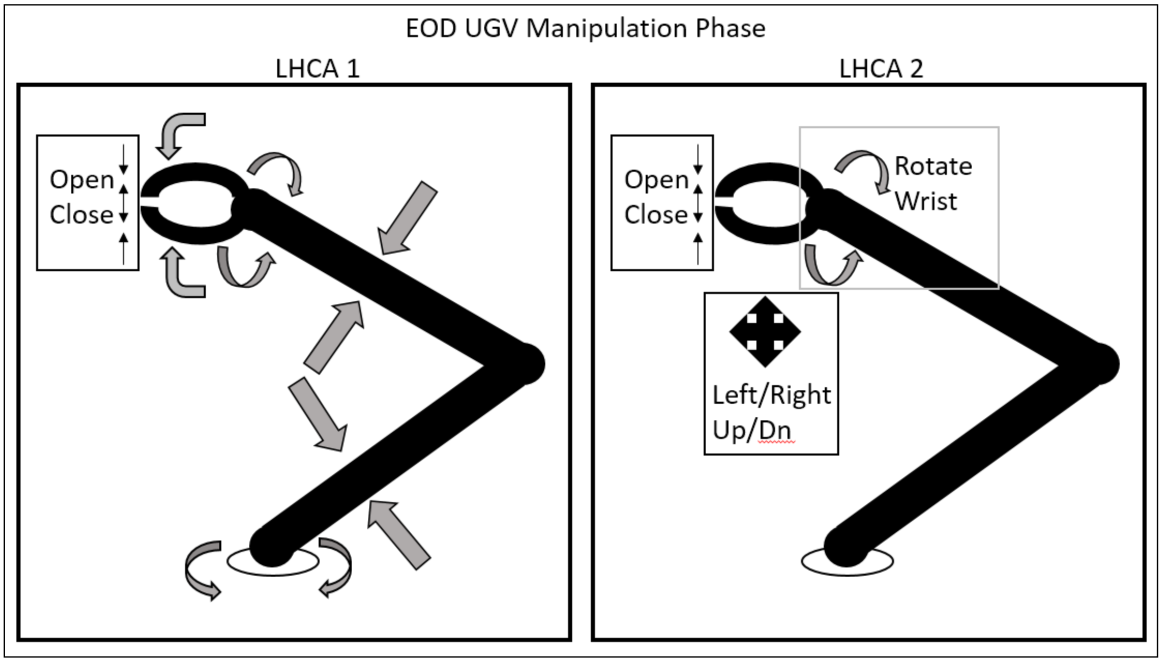

Figure 16– Difference between LHCA 1 and 2 during manipulation phase for the EOD UGV

If the EOD UGV is operated in the Parametric Control configuration during the manipulation phase, a set of challenges arise. The operator must give commands in the format of parameters for the UGV to achieve. An operator would provide a control input such as "move the manipulator arm down 4 inches" and the UGV would respond appropriately with an action. To be clear, the control input described could be given with just a few key strokes or a dial, but the information passed would be the control input described above. The operator would need to repeat this process until the gripper was closed on the device and the arm could be retracted for transit. This process becomes even more challenging if the device is not in the open, but is behind some sort of immovable obstacle. In such a case the operator would need to give many detailed control inputs to maneuver the arm around the obstacle and then grab the device.

The Parametric Control configuration is interesting because of the high level of detail the manipulation phase demands. A classic example of LHCA 3 is an autopilot system where the operator enters parameters for the vehicle to maintain and then takes a monitoring role. This is an effective implementation of control at LHCA 3 because the time required between control input is usually on the order of minutes or hours. In the case of the EOD UGV during the manipulation phase a Parametric Control scheme a very short period of time between control inputs is required. This issue was discussed further in Chapter 6.

When the UGV is operated in the Goal Oriented Control configuration the operator provides a single command to grab the ordinance and lift it, this may be done with a few button presses on a touch screen video feed. With this single command the UGV will move the arm and gripper to grasp and lift the ordinance.

As discussed in the Transit Phase section, LHCA 5 cannot be decomposed into two phases. Therefore, it will not be further discussed in the Manipulation phase.

In summary, the analysis of hypothetical systems included the development of a system configuration corresponding to each LHCA. Each configuration was then analyzed within the LHCA conceptual framework. These hypothetical systems demonstrated how a system could be operated at each LHCA. The functional analysis showed how cognitive tasks associated with tele-robotic control are allocated between the system and the operator at each LHCA. With each increase in LHCA, more cognitive tasks were allocated to the system, alleviating the operator from those task.

4. Breadth of Applicability of the LHCA framework

A major purpose of the LHCA conceptual framework is to provide a means for classifying the level of detail of control inputs an operator provides to a tele-robot or vehicle. Therefore, it is important to the LHCA framework's validity that a wide variety of vehicle and tele-robotic control methods can be classified. This requirement was successfully demonstrated by categorizing a variety of vehicle's and telerobotic control configurations across domains. In total, 42 real-world and hypothetical control configurations across six domains were categorized within the LHCA framework. The domains were: automobile, fixed wing aircraft, wheeled/treaded UGV, legged UGV, fixed wing UAV, and multi-rotor UAV. While the control configurations categorized were obviously not exhaustive, they do demonstrate that the LHCA framework can be applied to classify a wide variety of control configurations relevant to systems in motion.

5. Trends and Findings Regarding LHCA

To demonstrate that the LHCA framework is useful, trends and conclusions about control configurations associated with each level are important to understand. During analysis, two primary trends emerged: 1) as LHCA increases, the required level of human mental and physical effort, as well as attention decreases and 2) as LHCA increases operational flexibility decreases. In addition to the overall trends, each LHCA has associated traits. Those traits may make control of a system at a particular LHCA desirable for a user's needs. These traits and conclusion are described below.

Furthermore, during this research some notable topics related to LHCA were exposed. Discussion on liability and accountability issues related to LHCA, how mission requirements can affect the appropriate LHCA, the relationship between system complexity and LHCA, and the relationship between LoA and LHCA add additional insight to this analysis.

LHCA, Responsibilities, and Human Attentiveness

Every system has an associated set of responsibilities delegated to either the operator or the system to ensure effective operation. As LHCA increases, responsibilities are reassigned from the operator to the system. This reduction in operator responsibility directly leads to a reduction in the number of required human control inputs. Correspondingly, the amount of required human attention decreases as LHCA increases because operator responsibility decreases. As the level of detail of control inputs decreases the operator can devote less attention to controlling the motion of the system. The decrease in human attention may correlate to a decrease in workload and the ability to dedicate attention to other duties, including maintaining SA or other system aspects. Follow on research should investigate these potential relationships.

At LHCA 1 and 2 continuous control inputs are required. The operator must be able to continually monitor some aspect of the system or environment and remain constantly physically engaged with the system, which requires a high degree of attention.

The implication of this is easily illustrated with car accident statistics because most cars are operated at LHCA 1. According to the United States Department of Transportation 10% of all fatal crashes in 2014 involved a distracted driver (Highway Traffic Safety Administration & Department of Transportation, 2014). In these accidents, the amount of attention devoted to the task of driving by the vehicle operators dropped below the required threshold at the time of the accident.

At LHCA 3, the operator provides discrete control inputs. Some responsibilities have been delegated to the system at LHCA 3, such as maintaining parameters, but the operator remains fully responsible for monitoring the system during operation. This allows the operator some freedom to reallocate attention away from the task of controlling the system. For example, a pilot may briefly review airfield specific landing procedures while operating an aircraft at LHCA 3 during the cruise phase of flight. In this scenario, the pilot is still responsible for ground and aircraft collision avoidance, but because those hazards are predictable and low threat when properly deconflicted, the pilot can split attention between system operation and landing preparation.

When operating at LHCA 4 and 5, control of the motion of the vehicle requires even less attention from the operator because safety monitoring tasks have also been delegated to the system. A great example of this is a video capture multi-rotor UAV tracking the operator as they engage in a recreational activity. Once the system is activated, the operator may be skiing or rock-climbing, devoting no attention whatsoever to the system. The operator is completely free to complete other tasks while the system maintains video tracking, ground/obstacle avoidance, and battery/fuel monitoring responsibilities.

LHCA and Operational Flexibility

Another major trend is the correlation between LHCA and operational flexibility. In this context, the term operational flexibility refers to a system's ability to be used as required by the operator, even if that is outside of normal operations. At LHCA 1, the operator has complete control over the system; at LHCA 5, the operator is not even required to know what a system is doing on a moment-to-moment basis and the system may not be able to perform tasks it was not initially designed for. At higher LHCA the operator may not be able to provide a fine enough level of detail of control inputs to accomplish a mission as desired. Therefore, there is a negative correlation between LHCA and operational flexibility.

In his book, The Design of Everyday Things, Norman discusses a concept very similar to this negative correlation between LHCA and flexibility. He compares a concept of activity-centered controls to one of device-centered controls. Activity-centered controls are controls where inputs are provided based on the mode of operation. Device-centered controls are controls where inputs are given based on a system's sub-system metrics. Norman's activity-centered controls are equivalent to operating a system in LHCA 4, providing goals the system should achieve. Whereas Norman's device-centered controls are more like LHCA 1, providing inputs directly to how a system's components should behave. As Norman points out, activity-centered controls are very convenient when a system is operating normally, but can be frustrating and limit the flexibility of a system when abnormal operations are required (Norman, 2013).

Consider a case where a test of an aircraft's stall performance was desired. An example of a LHCA 2 system might be a stall protection system, preventing the operator from stalling the aircraft by mandating thrust and pitch limits. If the stall protection system were active on the aircraft when stall performance was to be tested the operator would need to disable the system before the test could be performed. In this example, the LHCA must be reduced to provide the flexibility required to accomplish the desired test mission.

Another example of the loss of flexibility at higher LHCA is the F-16 Auto-GCAS. This system will prevent a gear up landing by initiating a pull up maneuver before touchdown. However, if a malfunction were to occur to the aircraft's landing gear and a gear-up landing was required to recover the aircraft, the Auto-GCAS system would interfere. On 27 February, 2007 A Dutch F-16 Block 20 experienced a loss of nose gear during takeoff and needed to conduct a gear-up landing. After the mishap, the aircraft was safely recovered, repaired, and returned to service (Federal Aviation Administration, 2016a). If the Auto-GCAS were enabled, with the system controlled at LHCA 3, the aircraft might not be permitted to conduct the required maneuver.

As the LHCA for a system increases, more detailed decisions about how a system should behave are delegated to the system. The removal of the operator from the decision loop reduces the operator's ability to precisely control the system. If a mission is to operate outside of standard operating procedures, a lower LHCA may be required unless the system can be modified to support the alternate mission.

LHCA, HSI, and Other Traits

This section describes traits associated with each LHCA as well as some anticipated HSI effects of LHCA. The anticipated HSI effects of LHCA were not verified in this research, but are posited to be present. Follow on research should investigate the effects described in Table 8.

When conducting a cost-benefit analysis the traits described above should be considered. Table 8 could be used by system designers to select the appropriate LHCA(s) for a system under design. It should be noted that these traits should be considered relative. That is, if a particular system were to be configured to be operated at a LHCA, the traits apply relative to other configuration options. The traits do not apply when comparing one system to another. For example, an aircraft controlled at LHCA 3 may require more training than an automobile controlled at LHCA 1. However, an aircraft controlled exclusively at LHCA 3 would require less training than the same aircraft which is expected be controlled at LHCA 1.

Table 8 – LHCA Traits

	Level of Human Control Abstraction				
	1, Direct Control	**2, Augmented Control**	**3, Parametric Control**	**4, Goal Oriented Control**	**5, Mission Capable Control**

Operator Attention Required	**Maximum operator attention is required**, the system will not provide any control assistance and the operator must be attentive.	The operator must maintain constant awareness of the system and environment, some control assistance **may reduce some peak attention scenarios**.	The **operator may reduce attention to perform auxiliary tasks,** however, remains responsible for system safety and must be available to intervene if necessary.	The **operator's required attention is dramatically reduced**. The operator must be available to provide intermediate goals, but has relinquished safety responsibilities.	The **operator could potentially be completely inattentive** of the system during the mission.
Operator Control and System Flexibility	**Maximum control and flexibility** is given to the operator.	Operator maintains a **high amount of control and flexibility**, may not be suitable for some unique uses.	The **operator maintains control over most behavior** of the system, but **sacrifices precise control** for less control inputs.	**Flexibility is dramatically reduced**. If the system is not pre-programed or capable of self-adaptation to complete a task it cannot be completed.	Flexibility is reduced relative to LHCA 4. The system must be preprogramed or capable of self-adaptation and the **operator must know the full mission requirements before execution**.
Personnel Availability	Maximum demand and responsibility is placed on operator, this may result in a **smaller personnel pool** to draw from.	A high amount of responsibility is placed on the operator, **personnel pool will remain reduced**	Constant attentiveness and a 'feel' for control of the system are not necessary, the **personnel pool size increases** over LHCA 2.	Personnel availability is greatly increased. Virtually any responsible person who can select goals necessary to perform a mission should be able to operate the system. At LHCA 4 and 5 **a single operator may be capable of controlling multiple systems simultaneously**. This could increase personnel availability.	

System Knowledge and Training Requirements	**Training requirements will be highest** at this level, the operator must understand precisely how the system functions for maximum effectiveness.	**Training requirements will remain high**, but less understanding of subsystems is required.	**Training requirements are reduced** because the operator does not need to gain muscle memory of control movements, system understanding is reduced to knowledge of system capabilities.	**Training requirements** and system knowledge are both **dramatically reduced**. The operator only needs to know the system's capabilities and mission requirements.	System Knowledge and **Training Requirements are the reduced below that of LHCA 4** because an operator is not required to form sub-mission goals.
General Comments	**Unstable systems should not be operated at this level.**	In most applications where continuous control inputs are used, **Augmented Control is desirable instead of Direct Control**. However, the cost of implementing is usually greater than Direct Control.	This LHCA is **not suitable for applications where a high level of detail is required**, the best use is applications where system parameter stability for a long period of time is desirable.	During operations, it is possible the **operator may be available for other tasks**, depending on the time between intermediate goals assigned to the system.	It is very likely that a single **operator could control multiple systems** at this LHCA because the operator will not be involved in system control unless a failure occurs

Table 8 includes information on the correlation between LHCA and operator attention, operational flexibility, personnel availability, training requirements, and some general comments. The negative correlations between LHCA and operator attention as well as operational flexibility were discussed in detail above.

A positive correlation between the available personnel pool and LHCA is anticipated because the demand on the operator is decreased as LHCA increases. The number and challenge of physical and mental activities an operator must be capable of decreases as LHCA increases. With less challenge, it is likely that more people will be able to operate a system with a higher LHCA. This leads to a potentially larger pool of personnel to draw from to operate any given system.

A negative correlation between LHCA and required system knowledge and required training is also anticipated. With a more manual system the operator must have a better understanding of not only what a system can do, but how it functions. This is because at a higher LHCA the system filters the operator's control inputs, avoiding potential failure modes, but at lower LHCA the filters are removed. At lower LHCA the operator must have a better understanding of how to avoid potential failures. Additionally, at LHCA 1 and 2, the operator is providing continuous control inputs, often these types of control inputs are associated with acquiring a skill to operate the system effectively. Understanding not only how the system should move, but how the operator must move to effectively achieve those system movements can take time to perfect. Gaining a 'feel' for the controls and the associated muscle memory may take more time then entering discrete control inputs.

The general comments described in Table 8 are conclusions that emerged from the discussion in Chapter 5. The assertion that unstable systems should not be operated at LHCA 1 is justified because unstable systems such as the bipedal UGV and the B-2 must use at least LHCA 2 to avoid falling or crashing. Generally, LHCA 2 is desirable over

LHCA 1 except when development of the control system cost is prohibitive. This is because the operator is usually able to effectively maneuver the system as desired at LHCA 2 and often the challenge of operation would be reduced. LHCA 3 is not suitable for applications where a high level of detail is required because the operator must repeatedly input discrete control inputs to achieve the goal. The manipulation phase of the hypothetical EOD UGV was a good example of how operating a system at LHCA 3 in a high detail environment can present challenges. The general comment assertions about LHCA 4 and 5 are justified because of the reduced operator attention associated at LHCA 4 and 5. With the task of system control demanding less of the operator's attention at these LHCA, the operator may be available to perform other tasks or to operate more than a single vehicle.

It should be noted, however, that this discussion assumes that a system employs only a single LHCA. As was demonstrated with many of the real-world systems and all three of the hypothetical systems, often LHCA is dynamic, changing as appropriate during operations. A designer may consider that by adding the capability of a system to be operated at additional LHCA, their system could be operated at each LHCA, as desired. The operator could dynamically switch between LHCA at any given time, gaining the best traits from each LHCA for the situation.

Discussion on Liability and Accountability Issues Related to LHCA

Some confusion may arise when making the distinction between Parametric Control (LHCA 3) and Goal Oriented Control (LHCA 4) because of the potential ambiguous distinction between responsibilities allocated to either the operator or the system. This distinction is complicated further when legality and liability are involved. Aspects of control, authority to act, may be delegated to the system, but the operator may still be held accountable for the system's performance.

This is a major issue facing society at large as the capability arises to create systems which, from a technical perspective, could be operated at LHCA 4 or 5. These systems may not be allowed to operate at LHCA 4 or 5, assigning safety related responsibly to the system, because of regulatory issues. System manufacturers may never be willing to accept legal responsibility for their products actions, when their common use will involve delegating all control authority to the system.

Part of the purpose of the LHCA framework is to provide a lens through which the way a system is controlled can be considered, resulting in clear and meaningful distinctions between levels from the operator's perspective. The distinctions between the levels are intended to not be a technical assessment of how a system functions, but how the operator controls it. The important distinction between liability for accidents falling on the system operator, or not, incentivizes a certain level of attentiveness from the operator.

This generates an issue for the LHCA framework, the technical capabilities of systems enable possible operations at LHCA 4 or 5, but regulations and a clear understanding of how to ensure safety are currently lagging. For example, many automated driving features alleviate control tasks from the operator without accepting any legal responsibility. A case in point is Tesla Motors' Enhanced Autopilot feature which can replace the operator's steering, throttle, and brake control inputs, leaving the operator with no continuous control inputs while the system is activated. At the same time, Tesla does not legally accept responsibility for car accidents caused while the system is activated. While the system may, now or in the near future, be technically capable of being allocated safety related tasks, and indeed has even been allocated all control tasks, the system cannot be considered to be operating at LHCA 4 because safety responsibilities have not been removed from the operator.

The DJI Phantom described earlier may operate at LHCA 4 and 5 because the operator is issuing commands in a Goal or Mission oriented manor. However, accident accountability is unclear in at this point. For example, the 2016 FAA document intended to regulate small UAS operations states "Autonomous operations have numerous practical applications, including agricultural operations, aerial photography, and search and rescue. The FAA agrees with the commenters who pointed out that the ability for a small unmanned aircraft to fly autonomously could add significant utility to a small UAS operation and would further encourage innovation in the industry. Accordingly, this rule will allow the autonomous flight of small unmanned aircraft." Assignment of liability in the case of an accident with an autonomous UAS was not addressed, however the FAA emphasized that the operator must be able to command the UAS to land, if required. (Federal Aviation Administration, 2016b)

The severity of a mishap may be a large factor in this area. A small UGV traveling at a low velocity may have very little safety related concerns and therefore an operator may be willing to decrease the level of detail of control inputs to LHCA 4 more easily. As autonomous systems and their operations are further developed, this will be a key point of interest. A social, legal, or regulatory system must be developed before operations at LHCA 4 or 5 will be made available for a broad variety of systems.

Discussion of Mission Requirements and LHCA

The majority of the discussion relating to LHCA was associated with different configurations of systems because a system's available control inputs affect LHCA. However, mission requirements may also affect which LHCA is possible and optimal. The amount of information available to an operator before a mission will affect whether LHCA 5 is an option. For an operator to control a system at LHCA 5 they must know generally what must be done during a mission, but that is not always the case.

Consider a common dynamic ground support mission a bomber might fly over hostile territory. The aircraft may be assigned to enter a holding pattern over an area where combat is expected, then await further orders to support ground operations. The bomber may drop no ordinance or may drop all its ordinance, possibly even meeting up with an aerial refueling tanker to extend its mission if required. This type of dynamic mission where the mission requires follow-on orders is not possible at LHCA 5 because intermediate orders are core to the mission.

Discussion on System Complexity and LHCA

Interestingly, the complexity of a control system is not a factor in determining the LHCA a system is controlled at. For example, the CMU HRP was operated at LHCA 2, enabled by an algorithm which determined how the system moved. This complex algorithm, which was technically challenging to implement, enabled the system to operate only at LHCA 2, even though many autopilot systems are much simpler and provide a LHCA 3. Similarly, the fly-by-wire systems discussed earlier are complex and take many sensors with complex algorithms to implement, but again are operated at LHCA 2 while more simplistic systems, which simply regulate parameters are operated at LHCA 3. This is because the level of detail of control inputs provided by the human is higher with the LHCA 2 systems than with the LHCA 3 systems. It is important to remember that the LHCA conceptual framework focuses on the operator's control inputs, not the technical complexity of the system being controlled.

Relationship between LoA and LHCA

The relationship between LoA and LHCA seems to have a loose positive correlation. LoA has a focus on the authority granted to a system to make a decision without human verification of that decision. LHCA has a focus on the level of detail of decisions made by the operator. Thus, from a system design perspective, LoA is focused on operator oversight, whereas LHCA is focused on human-machine interface/communication. For LoA and LHCA, the low and high end of the scales are very similar (assuming that LoA is applied to a control system of a system in motion): systems are controlled completely manually or completely autonomously. However, the increments between are quite different.

The LoA framework is designed to apply more broadly then the LHCA framework. The LoA framework can be useful in describing the level of automation for a range of technologies which implement some function that could be performed by a human. However, the LHCA framework has the limited scope focusing on vehicles and tele-robotics and applies at the system level or system state level. That is LHCA is not defined when analyzing a technology which automates as subfunction in the functional hierarchy associated with controlling the motion of systems.

Other differences between these frameworks are the focus, differentiations between levels, and the fact that the LoA framework does not evaluate the types of decisions it is assessing. The focus of the LoA framework is the system while the focus the LHCA framework is on the operator. The differentiations between levels in the LoA framework are determined by the required oversight the system requires while the LHCA framework focuses on the level of detail of decisions made by the operator. Finally, the LoA framework does not evaluate the type of decision which is automated, while the types of decisions allocated to the system or the operator are very important in assessing a LHCA.

This is not to say the that LoA framework is not useful in assessing system effectiveness. There are applications where the proper oversight of decisions made by a system is an important trait that must be discussed. For example, if an autonomous UAV were to be sent on a strike mission to attack a ground target, it is probably appropriate to have some human oversight within the kill-chain. That level of human oversight can be described with the LoA framework. Leadership may decide to require a human have veto power over the decision to fire, LoA 6. Alternatively, leadership may decide that the appropriate oversight for the human operator to initiate the ‘fire’ decision, LoA 5. In either of these cases the LoA framework describes exactly that type of human oversight. Another example where a different level of operator oversight would be appropriate is a missile defense system. Likely, leadership would want to allocate a large amount of autonomy to the system and not require operator oversight to initiate countermeasures. Therefore, LoA of 10 might be specified as a design constraint.

The two frameworks, LoA and LHCA, describe different aspects of controlling a system and both have their place. LoA describes the authority granted to a system, whereas LHCA describes the level of detail of control inputs provided by the operator.

6. Evaluation of LHCA as a Scientific Theory

By applying the criteria developed by Jacobs and Grainger just as de Winter did to evaluate Fitts list, the LHCA conceptual framework can be evaluated as a scientific theory (de Winter & Dodou, 2014). Unfortunately, as this document introduces the LHCA framework, not all the criteria can be applied. Specifically, the interpretability of the LHCA framework cannot yet be evaluated because the framework has not been applied by other researchers. Further, generalizability cannot be fully evaluated as unknown systems have yet to be generated. Follow-on research should evaluate these aspects of the framework. The other remaining criteria were assessed below:

Plausibility – The primary assumption of this research is that as the LHCA increases the amount of operator attention required for system control decreases. This decrease in required operator attention will likely result in a reduction in workload. This is consistent with Endsley's concept of Control Granularity (Endsley, 2015). In addition, the transfer of cognitive tasks from the operator to the system is assumed to result in a reduction in workload for the operator as is consistent with the workload modeling literature. This consistency with other research suggests that the LHCA framework is plausible.

Explanatory adequacy – The framework lays out a basis for which the control of systems can be categorized by the level of detail of control inputs provided by the operator. This concept is consistent with the concepts discussed by Chen et al. (2007), Endsley (2015), and Milgram et al. (1995).

Simplicity – The framework consists of five levels and has been shown to permit the classification of 42 system control configurations within 11 different systems within 7 different domains through the application of a decision tree having only four questions. There are also not a series of exceptions and situational rules which would add complexity to the framework.

Descriptive Adequacy – The framework categorized the control of systems across domains. Those categorizations were useful and had meaning because conclusions about a system operating at a LHCA could be drawn. Those conclusions were reasonable and aligned with data observed about the operation of those systems.

Generalizability – The framework was used to classify many systems, including hypothetical systems. At this point, it is not possible to say that the LHCA framework is generalizable to any future vehicles or tele-robotic systems. However, it is conceivable that the framework could be applied to existing and foreseeable future systems within its scope.

The LHCA framework has been shown to meet five of the six criteria established by Jacobs and Granger and applied by de Winter (de Winter & Dodou, 2014; Fitts, 1951; Jacobs & Grainger, 1994). The sixth criteria, interpretability, should be evaluated with follow-on research.

7. Summary of Analysis

This analysis covered the assessing of LHCA for both real world and hypothetical systems, the effect of LHCA on system level traits, and LHCA evaluated as a scientific theory. It was shown that the LHCA can be applied broadly and the LHCA of a control configuration does have a system level effect. The evaluation of the LHCA conceptual framework as a scientific theory showed that, while interpretability has not yet been assessed, the LHCA framework has an acceptable academic pedigree.

VI. Conclusions and Recommendations

1. Introduction of Conclusions

This chapter will summarize the results and overall conclusions of this research. The LHCA conceptual framework will be evaluated against the recommendations of the DSB (Office of the Under Secretary of Defense for Acquisition Technology Logistics, 2012). Finally, recommendations for follow-on research into the LHCA conceptual framework are proposed.

2. LHCA Alignment with DSB Recommendations

As discussed in chapter 1, the DSB proposed developing a framework that focused on capabilities, cognitive functional allocation, and the trade-space of a system operating at different levels within the framework (Office of the Under Secretary of Defense for Acquisition Technology Logistics, 2012). The LHCA conceptual framework was intended to adhere to these recommendations as closely as possible, providing a useful tool to the DoD.

The LHCA framework is designed to categorize the control of a system, therefor it is only able to express the capabilities of a system relating to the control of that system. A capability desired by the DoD is the ability to control multiple tele-robots simultaneously by a single operator (US DoD, 2005). As discussed previously, a system controlled at LHCA 4 or 5 could potentially be operated in this way because the demands on the operator's attention are relatively low. The LHCA framework applies broadly to vehicles and tele-robotic systems and these systems may have a myriad of capabilities.

The framework does not have a focus on evaluating the capabilities of a system, but within the range of control capabilities the LHCA adequately describes capabilities.

The LHCA focuses heavily on the functional allocation of cognitive tasks between the operator and the system. The very definitions of each level revolve around the level of detail of tasks that are allocated to the operator verses the system. The LHCA framework aligns well with this recommendation by the DSB.

As recommended by the DSB any useful framework must be able to make the system level trades visible. The LHCA framework achieves this goal through the initial correlations between LHCA and both operational flexibility and operator attention. It is also postulated that there are many other system level trades which could be made visible using the LHCA framework, especially in the field of HSI. Follow-on research is recommended to determine what the full trade-space is, but a foundation of potential system level trades at different levels of the LHCA has been established.

In conclusion, the LHCA framework fulfills the functional allocation and system level trade recommendations from the DSB. The narrow scope of control capabilities can also be assessed with the LHCA framework. Overall, the LHCA framework generally meets the requirements for an alternative to the LoA framework as recommended by the DSBs and can be used by the DoD and others as a tool when assessing human control of systems or when developing design requirements.

3. Proposed Follow-On Research

There are several opportunities for follow on research on the subject of LHCA. Research into potential HSI and human performance effects described in Table 8 is highly recommended. Quantitative research should be used to verify and categorized the intensity of these effects. As discussed above, a correlation between required operator attention and LHCA exists, it is likely that the reduction in required operator attention will correlate to a reduction in operator workload.

Research into the effect of LHCA on SA should also be conducted. The relationship between LHCA and SA may be complex. The operator's SA may be considered to have layers of detail similar to the concept of LHCA. For example, if the operator is flying an aircraft at LHCA 1, the operator may notice a tendency for the aircraft to drift in a certain direction. This drift may be negated by auto-trim features associated with LHCA 2. Therefore, an operator may lose SA on this very detailed aspect of aircraft performance. In contrast, if an operator were controlling an aircraft at LHCA 4, they may be able to maintain higher SA regarding the operational context. By focusing less on the details of the aircraft's performance, the operator may be able to have a better SA on the mission as a whole. Further research into both the concept of level of detail of SA and the effect of LHCA on that SA should be pursued.

Another area of research to be pursued in this area is the concept of level of detail of control inputs provided by the operator as applied outside the scope of vehicles and tele-robotics as examined in this research. An example of a system which could be assessed within the LHCA framework but is not a vehicle or tele-robotic system is a home thermostat. A home thermostat could be considered to receive parametric control inputs, turning on and of aspects of a heating, ventilation, and air conditioning system to regulate temperature. Another example is a handheld pistol-grip drill. This system could be considered to receive direct control inputs, the position of the trigger setting the precise motor power. This system may be considered to have augmented control if a torque clutch is added, where an operator specifies the maximum torque of the drill and the drill automatically disengages if that torque is reached. These concepts of level of detail of control inputs may be applicable more broadly then examined in this research and should be explored further.

Finally, a simple test of interpretability for the LHCA framework should be conducted. The proposed experiment would provide descriptions of control configurations and ask participants to classify an operator's LHCA. The robustness and repeatability of the LHCA framework could be tested in this experiment, demonstrating that the LHCA framework is understandable and interpretable. This test would be designed to show if a control system would be classified consistently within the LHCA framework independent of the person classifying the system.

4. Summary of Significant Findings & Insights

This research proposed a conceptual framework for analyzing the level of detail of control inputs an operator provides to vehicle and tele-robotic systems. The framework itself was then examined, showing that it could be applied both broadly and had the ability to make system level traits visible. The framework was also evaluated as a scientific theory, meeting all five of the criteria examined. Finally, the LHCA was assessed against the DSB’s recommendations. The framework was shown to illustrate control related capabilities, show cognitive task allocation between the operator and the system, and make system level traits visible.

Bibliography

American Automobile Association Foundation for Traffic Safety. (2017). FAQs: Anti-Lock Braking System (ABS) | AAA Foundation for Traffic Safety. Retrieved February 21, 2017, from https://www.aaafoundation.org/faqs-anti-lock-braking-system-abs

Beringer, D. B., & Harris, H. C. (1999). Automation in General Aviation : Two Studies of Pilot Responses to Autopilot Malfunctions. *The International Journal of Aviation Psychology*, *9*(2), 155–174. http://doi.org/10.1207/s15327108ijap0902

Chen, J. Y. C., Haas, E. C., & Barnes, M. J. (2007). Human Performance Issues and User Interface Design for Teleoperated Robots. *IEEE Transactions on Systems, Man and Cybernetics, Part C (Applications and Reviews)*, *37*(6), 1231–1245. http://doi.org/10.1109/TSMCC.2007.905819

Chestnutt, J., Michel, P., Nishiwaki, K., Kuffner, J., & Kagami, S. (2006). An intelligent joystick for biped control. *Proceedings - IEEE International Conference on Robotics and Automation*, *2006*, 860–865. http://doi.org/10.1109/ROBOT.2006.1641817

Clough, B. (2002). *Metrics, schmetrics! How the heck do you determine a UAV's autonomy anyway*. Wright-Patterson AFB, OH.

de Winter, J. C. F., & Dodou, D. (2014). Why the Fitts list has persisted throughout the history of function allocation. *Cognition, Technology and Work*, *16*(1), 1–11. http://doi.org/10.1007/s10111-011-0188-1

DJI. (2016). Phantom 4 Pro - Professional aerial filmmaking made easy. Retrieved January 12, 2017, from http://www.dji.com/phantom-4-pro

Draper, J. (1995). Teleoperators for advanced manufacturing: Applications and human factors challenges. *International Journal of Human Factors in*, *5*(1), 53–85. http://doi.org/10.1002/hfm.4530050105

Drone multicopter in field. (2017). Retrieved from https://pixabay.com/en/drone-field-multicopter-905955// - Free stock Photo

Endsley, M. R. (1987). The application of human factors to the development of expert systems for advanced cockpits. *Human Factors Society 31st Annual Meeting*, *31*(12), 1388–1392. http://doi.org/10.1177/154193128703101219

Endsley, M. R. (2015). *Autonomous Horizons: System Autonomy in the Air Force - A Path to the Future* (Vol. 1: Human-A).

Endsley, M. R., & Kaber, D. B. (1999). Level of automation effects on performance, situation awareness and workload in a dynamic control task. *Ergonomics*, *42*(3), 462–492. http://doi.org/10.1080/001401399185595

Endsley, M. R., & Kiris, E. O. (1995). The Out-of-the-Loop Performance Problem and Level of Control in Automation. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *37*(2), 381–394. http://doi.org/10.1518/001872095779064555

Federal Aviation Administration. (2016a). *Civil Airworthiness Certification, Former Military High-Performance Aircraft*. Washington D.C.: FAA.

Federal Aviation Administration. Operation and Certification of Small Unmanned Aircraft Systems, 81Federal Register. Federal Aviation Administration. 42063–42214 (2016).

Feigh, K. M. M., Dorneich, M. C. C., & Hayes, C. C. C. (2012). Toward a Characterization of Adaptive Systems: A Framework for Researchers and System Designers. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *54*(6), 1008–1024. http://doi.org/10.1177/0018720812443983

Fitts, P. (1951). *Human engineering for an effective air navigation and traffic control system*. *Ohio State Univ.* Columbus, OH.

Highway Traffic Safety Administration, N., & Department of Transportation, U. (2014). Research Note: Distracted Driving 2014, *2014*(April 2016).

Jacobs, A. M., & Grainger, J. (1994). Models of visual word recognition: Sampling the state of the art. *Journal of Experimental Psychology Human Perception and Performance*, *29*(6), 1311–1334.

Kaber, D. B., & Endsley, M. R. (2004). The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task. *Theoretical Issues in Ergonomics Science*, *5*(2), 113–153. http://doi.org/10.1080/1463922021000054335

Lorenz, B., Nocera, F. D., Röttger, S., Di Nocera, F., Rottger, S., & Parasuraman, R. (2001). The Effects of Level of Automation on the Out-of-the-Loop Unfamiliarity in a Complex Dynamic Fault-Management Task during Simulated Spaceflight

Operations, *45*(2), 44–48. http://doi.org/10.1177/154193120104500209

McSweeney, K. (2016). Automated drones navigate and inspect cell towers without GPS. Retrieved January 12, 2017, from http://www.zdnet.com/article/automated-drones-navigate-and-inspect-cell-towers-without-gps/

Milgram, P., Rastogi, A., & Grodski, J. J. (1995). Telerobotic control using augmented reality. In *Proceedings 4th IEEE International Workshop on Robot and Human Communication* (pp. 21–29). IEEE. http://doi.org/10.1109/ROMAN.1995.531930

Ministry of Transportation, J. (1996). *Nagoya A300 Accident Report*.

Norman, D. (2013). *The Design of Everyday Things* (Revised an). New York, NY: Basic Books.

Ntuen, C., & Park, E. (1988). Human factor issues in teleoperated systems. *Proceedings of the First International Conference*.

Office of the Under Secretary of Defense for Acquisition Technology Logistics. (2012). The Role of Autonomy in DoD Systems. *DoD Defense Science Board*, (July), 125. http://doi.org/10.1016/S0140-6736(02)11924-6

Parasuraman, R. (1986). Vigilance, monitoring, and search. In J. P. (Ed) Boff, Kenneth R. (Ed); Kaufman, Lloyd (Ed); Thomas (Ed.), *Handbook of perception and human performance, Vol. 2: Cognitive processes and performance* (pp. 1–39). Oxford, England: John Wiley & Sons.

Pitt, M. ., Myung, I. J., & Zhang, S. (2002). Toward a Method of Selecting Among Computational Models of Cognition, *109*(3), 472–491. http://doi.org/10.1037//0033-295X.109.3.472

Proud, R. W., Hart, J. J., & Mrozinski, R. B. (2003). *Methods for determining the level of autonomy to design into a human spaceflight vehicle: a function specific approach*. Houston, TX.

Riley, V. (1989). A General Model of Mixed-Initiative Human-Machine Systems. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *33*(2), 124–128. http://doi.org/10.1177/154193128903300227

Scerbo, M. W. (1996). Theoretical Perspectives on Adaptive Automation. In M. Parasuraman, Raja; Mouloua (Ed.), *Automation and Human Performance: Theory and Applications* (Vol. 514, pp. 37–64). Mahwah, New Jersey: Lawrence Erlbaum

Associates, Publishers. http://doi.org/10.1017/CBO9781107415324.004

Sheridan, T. B. (2011). Adaptive automation, level of automation, allocation authority, supervisory control, and adaptive control: Distinctions and modes of adaptation. *IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans, 41*(4), 662–667. http://doi.org/10.1109/TSMCA.2010.2093888

Sheridan, T. B., & Verplank, W. L. (1978). *Human and Computer Control of Undersea Teleoperators*. Cambridge, MA.

Small Motor Boat Waiting Ferry Passengers Stock Photo. (2017). Retrieved from https://pixabay.com/en/aquatic-bay-boat-craft-cross-1238422/

US DoD. (2005). Unmanned Aircraft Systems Roadmap 2005-2030, 1–62. http://doi.org/May 14, 2010

USAF. (2008). *Summary of Facts, B-2A, S/N 89-0127*.

Vagia, M., Transeth, A. A., & Fjerdingen, S. A. (2016). A literature review on the levels of automation during the years. What are the different taxonomies that have been proposed? *Applied Ergonomics*, *53 Pt A*, 190–202. http://doi.org/10.1016/j.apergo.2015.09.013

Vector - vector remote control rc transmitter black icon. (2017). Retrieved February 3, 2017, from http://www.123rf.com/search.php?word=airplane+radio&start=200&viewsubs=0&searchopts=&itemsperpage=100&sti=lst69rq0294f0vt0ds%7C&mediapopup=16161520

Welsh, M. (2015). *A Call to the Future: The New Air Force Strategic Framework. Senior Leadership Perspective*.

Wickens, C. D., Hollands, J. G., Banbury, S., & Parasuraman, R. (2015). *Engineering psychology and human performance*. (N. Roberts, Ed.) (3rd ed.). New York, New York, USA: Electronic Publishing Services Inc.

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 074-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of the collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to an penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
23 03 2017	Master's Thesis	Aug 2015 – March 2017

4. TITLE AND SUBTITLE	
A FRAMEWORK FOR ANALYZING AND DISCUSSING LEVEL OF HUMAN CONTROL ABSTRACTION	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER** 2016-067
Clifford, Johnson D., Captain, USAF	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way, Building 640 WPAFB OH 45433-8865	AFIT-ENV-MS-17-197
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) US Air Force Office of Scientific Research, Mathematical and Computational Cognition Program Attn: James H. Lawton, PhD 4075 Wilson Blvd., Suite 350 Arlington, VA 22203 (703) 696-5999 (DSN: 426-5999) James.Lawton.1@us.af.mil	**10. SPONSOR/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

It is often useful to understand the impact of an artificial teammate upon human workload in human-machine teams. Levels of Autonomy (LoA) differentiate systems based on control authority. Unfortunately, human workload is not necessarily correlated with LoA. An alternate classification framework, designated the Level of Human Control Abstraction (LHCA), is proposed. LHCA differentiates system states based on the control and monitoring tasks performed and the level of decisions made by humans. The framework defines five levels, designed to differentiate between system states based upon anticipated levels of human attention. This presentation will summarize the framework and demonstrate its application.

15. SUBJECT TERMS

Level of Autonomy, Human-Machine Communication

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Michael E. Miller, PhD
U	**U**	**U**	**UU**	110	**19b. TELEPHONE NUMBER** *(Include area code)* (937) 255-3636, ext 4651

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18